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Neural mechanisms involved in error processing: A comparison of errors made with and without awareness

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The ability to detect an error in one's own performance and then to improve ongoing performance based on this error processing is critical for effective behaviour. In our event-related fMRI experiment, we show that explicit awareness of a response inhibition commission error and subsequent post-error behaviour were associated with bilateral prefrontal and parietal brain activation. Activity in the anterior cingulate region, typically associated with error detection, was equivalent for both errors subjects were aware of and those they were not aware of making. While anterior cingulate activation has repeatedly been associated with error-related processing, these results suggest that, in isolation, it is not sufficient for conscious awareness of errors or post-error adaptation of response strategies. Instead, it appears, irrespective of awareness, to detect information about stimuli/responses that requires interpretation in other brain regions for strategic implementation of post-error adjustments of behaviour.

Keywords: Neural mechanisms; Error processing; fMRI

Introduction

Our ability to monitor ongoing performance is an executive function critical to behavioural control, in particular the processing of errors, which serves an adaptive function in signalling to an individual that an ongoing task has increased in difficulty and that the intervention of other attention or control processes would potentially be advantageous (Gehring et al., 1993; Ullsperger and von Cramon, 2001). The neural basis of error-processing has become a key research interest in cognitive neuroscience, not only because of its importance to these cognitive skills and to the mechanisms by which cognitive control is implemented, but also because understanding its cortical network may offer insights into the dysfunctions of self-monitoring seen in a range of clinical conditions (Carter et al., 2001; Forman et al., 2004; Gehring et al., 2000; Kaufman et al., 2003; Mathalon et al., 2003). Studies of neural responses to performance errors have suggested that the prefrontal (PFC) and anterior cingulate (ACC) cortices are critical to error processing (Garavan et al., 2003), but the precise roles these regions play remains debated (Bush et al., 2000).

To date, neuroimaging studies have focussed primarily on identifying the neural regions involved in error detection (Kiehl et al., 2000; Menon et al., 2001). An important distinction exists between error detection and error awareness. The cognitive neuroscience theories that characterise how a performance error is processed by the brain focus almost exclusively on error detection, without assuming that an individual is conscious of this process (see Yeung et al. (2004) for an interesting exception). It is therefore possible for an error to be detected by the brain and behavioural correction to occur, without the individual being aware of either phenomenological experience. For the purposes of this study, error awareness is defined as the explicit recognition of a performance error via a specific 'awareness' button press response. Nieuwenhuis and colleagues (2001) were the first to examine the neural correlates of error awareness, identifying with event-related potentials (ERPs) that the error-negativity (Ne/ERN), typically localised to the ACC region and associated with error detection (Dehaene et al., 1994; Gehring et al., 1993; Scheffers et al., 1996), following unperceived eye-movement errors did not correspond with conscious awareness of an error. Rather, another ERP component, a positivity associated with errors or Pe, directly related to error awareness. The Pe is argued to be a P3-like

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positivity that is maximal at midline parieto-central scalp sites (Falkenstein et al., 2000; Vidal et al., 2000).

The site and specificity of the error positivity response is of great interest, as it may reveal cortical regions critical to error awareness. Previous studies attempting to localise the source of the Pe response have yielded mixed results, finding a distribution of sites that included dorsolateral, cingulate, mesiotemporal and orbitofrontal cortex using intracranial recording (Brazdil et al., 2002), while ERP source localisation studies have typically suggested ACC generators (Herrmann et al., 2004; van Veen and Carter, 2002). One limitation of these three studies was the absence of the type of 'awareness' comparison performed by Nieuwenhuis et al. (2001) between errors recognised by participants and those of which they remained unaware. The specificity of this response and its likely cortical generator are of great interest, as researchers have already begun to probe the neurobiological basis of error processing deficits (including error awareness) in clinical conditions such as Alzheimer's disease and schizophrenia by measuring the Pe (Mathalon et al., 2002; Mathalon et al., 2003).

Here, we utilised the higher spatial resolution of fMRI to address the neural mechanisms that are associated with error awareness and post-error behaviour.

Methods

Subjects

Thirteen subjects (6 female, mean age 28, range: 21–41) participated in the experiment; all were right-handed and reported no history of neurological symptoms. Subjects were fully informed of the nature of the research and provided written consent for their involvement in accordance with the Institutional Review Board of the Nathan Kline Institute.

Behavioural task

To examine conscious recognition of errors, we developed the Error Awareness Task (EAT) (see Fig. 1), a motor Go/No-go response inhibition task in which subjects make errors of commission of which they are aware (Aware errors) or unaware (Unaware errors). The task presents a serial stream of single colour words in congruent fonts, with the word presented for 900 ms followed by a 600 ms inter-stimulus interval. Subjects were trained to respond to each of the words with a single 'Go trial' button press and withhold this response when either of two different circumstances arose. The first was if the same word was presented on two consecutive trials (Repeat No-go), and the second was if the word and font of the word did not match (Stroop No-go). By having competing types of response inhibition rules, we aimed to vary the strength of stimulus–response relationships, whereby representations of rules competitively suppress one another such that the more prepotent rule would suppress the weaker rule and so produce a significant number of errors, a small proportion of which may go unnoticed due to focussing primarily on the prepotent rule. In particular, we aimed to capitalise on the overlearned human behaviour of reading the word rather than the colour of the letters (the Stroop effect) and so predispose subjects to monitor for the Repeat rather than the Stroop No-gos. Subjects were trained to press a different 'error awareness' button on the trial following any commission errors and were not required to make the standard Go response.

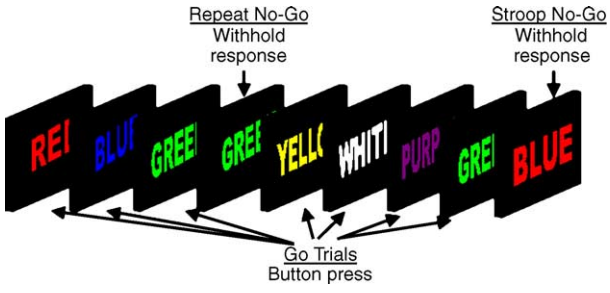

Fig. 1. The Error Awareness Task required subjects to respond with a button press to a stream of colour words and withhold their response when either a word was repeated on consecutive trials or the font and word were incongruous. Subjects were trained to press a different button following any commission errors.

An 'Oddball condition' was also administered to identify activations associated with the changed response demands of the Aware errors. This condition replicated the stimuli and timing from the EAT task except that No-go trials were replaced with the word 'STOP'. Subjects were instructed to respond to each trial with the 'Go trial' button and press the 'error awareness' button on the trial following 'STOP' stimuli, though they were not required to inhibit their response to the 'STOP' trials. Oddball events therefore represented similar response and decision requirements to Aware errors, without the subject making an error.

Six blocks (5 EAT and 1 Oddball) of 225 trials were administered to subjects during fMRI data acquisition. An event-related design was employed, distributing 128 No-go events pseudo-randomly throughout the serial presentation of 1125 Go trials, having the dual advantage of mixing frequent responses and infrequent response inhibitions to maintain response prepotency and separating the events of interest sufficiently so that correct and failed response inhibition events could be analysed separately without signal cross-contamination. Subjects were informed prior to the final block of trials that the Oddball condition was to begin, which contained 25 Oddball trials distributed within 225 Go trials.

Scanning parameters

All scanning was conducted on a 1.5 T Siemens VISION scanner in which foam padding was used to restrict head movements. Contiguous 5 mm sagittal slices covering the entire brain were collected using a single-shot, T2*-weighted echo planar imaging sequence (TE = 50 ms; TR = 2000 ms; FOV = 256 mm; 64 × 64 mm matrix size in-plane resolution). High-resolution T1-weighted structural MPRAGE images (FOV = 256 mm, isotropic 1 mm voxels) were acquired following functional imaging to allow subsequent activation localisation and spatial normalisation. Stimuli were delivered using an IFIS-SA stimulus-delivery system (MRI Devices Corp., Waukesha, Wisconsin), which was equipped with a 640 × 480 LCD panel. This shielded LCD screen is mounted on the head-coil, directly in the subjects' line of vision.

All analyses were conducted using AFNI software (Cox, 1996). Following image reconstruction, the time-series data were time-shifted using Fourier interpolation to remove differences in slice acquisition times and motion-corrected using 3D volume registration (least-squares alignment of three translational and three rotational parameters). Activation outside the brain was also removed using edge detection techniques. No subjects showed

significant residual motion, thus allowing all 13 to be included. Although the stimulus stream was presented at 1.5 Hz, all events of interest were time-locked to the beginning of the 2-s whole-brain volume acquisition during presentation of the task (every four trials in the presentation sequence, the beginning of a trial would coincide with the beginning of the 2-s TR cycle, e.g., trial 1–0 s, 2–1.5 s, 3–3 s, 4–4.5 s, 5–6 s, 6–7.5 s, 7–9 s, 8–10.5 s, 9–12 s).

Separate haemodynamic response functions at 2-s temporal resolution were calculated using deconvolution techniques for successful response inhibitions (Stops), Oddball events and commission errors of which subjects were either aware (Aware errors) or unaware (Unaware errors). A non-linear regression program determined the best-fitting gamma-variate function for these IRFs (Cohen, 1997) as previously described (Garavan et al., 1999). The area under the curve of the gamma-variate function was expressed as a percentage of the area under the baseline, which for this task was the ongoing trial period (Go trials) activity. Therefore, the activation during events of interest represents activity over and above that required for the ongoing trial period (or Go) responses. The group map for Oddball trials included only 12 subjects; a technical difficulty resulted in button press responses not being recorded during data acquisition for one subject's Oddball condition.

The percentage area (event-related activation) voxels were re-sampled at 1 mm^3 resolution then warped into standard Talairach space (Talairach and Tournoux, 1988) and spatially blurred with a 3 mm isotropic rms Gaussian kernel. Group activation maps were determined with one-sample t tests against the null hypothesis of zero event-related activation changes (i.e., no change relative to baseline). Significant voxels passed a voxelwise statistical threshold (t = 3.425, P = 0.005) and were required to be part of a larger 280 μl cluster of contiguous significant voxels. Thresholding was determined through Monte Carlo simulations and resulted in a 5% probability of a cluster surviving due to chance.

The primary comparison of interest was to identify differences in activation between Aware and Unaware errors. The activation clusters from whole-brain analyses of both Aware and Unware errors (see Table 1) were used to create an OR map for the purposes of an ROI analysis. An OR map includes the voxels of activation indicated as significant from either of the constituent maps. The mean activation for clusters in the combined map was then calculated for the purposes of an ROI analysis, deriving mean activation levels for Aware and Unaware errors that were compared using repeated measures t tests, corrected via a modified Bonferroni procedure for multiple comparisons (Keppel, 1991). This approach was taken due to the relatively small number of unaware error events, which previous research suggests will influence the spatial extent of activation (Huettel and McCarthy, 2001; Saad et al., 2003), rather than the level of activation in pre-defined ROI-type analyses (Hester et al., 2004). An additional examination of midline activation patterns during Aware and Unaware errors was also performed using an ROI derived from our meta-analysis of No-go errors (Hester et al., 2004) (n = 44), which had its centre of mass located in the dorsal ACC region, but also included activation in the pre-SMA region. This dorsal ACC/pre-SMA region was of interest due to the previous studies that have identified its activity during error processing (Garavan et al., 2003; Ridderinkhof et al., 2004; Ullsperger and von Cramon, 2001).

Table 1
Regions of event-related activation during Aware errors

Structure	Brodmann's area	HS	Vol (μl)	Centre of mass			P
				x	y	z	
Frontal lobe							
Superior frontal	10	L	894	−26	53	3	
	10	R	351	34	49	−2	
	9	R	460	19	41	37	*
Superior/medial frontal	9/8	R	457	11	51	27	
Precentral	9	L	569	−36	23	38	
Middle frontal	6	R	368	35	12	47	
Middle/inferior frontal	11/47	L	331	−37	36	−10	*
Inferior/superior temporal	47/38	L	947	−40	16	−18	*
Anterior cingulate	32	R	506	3	40	20	
Parietal lobe							
Inferior parietal	40	L	6988	−46	−50	39	*
	40	R	3189	46	−48	39	*

Asterisk represents ROIs that showed significantly greater activation during Aware errors compared to Unaware errors ($P < 0.05$, corrected).
Positive values for x, y and z coordinates denote, respectively, locations that are right, anterior and superior relative to the anterior commissure.

To confirm that activation seen during Aware errors did not represent the changed response demands (i.e., altering the response to indicate awareness), the Aware ROIs were used to compare mean activation levels for Aware errors and Oddball trials.

Results

Subjects correctly withheld their responses during 61% of No-go trials, with performance on Repeat No-gos significantly better than Stroop No-gos (70% vs. 48%), $t(12) = 5.74$, $P < 0.01$. On average, subjects reported being aware of 70% of errors (range = 15%–93%), with 52% of Aware errors occurring on Stroop No-gos. Of the 30% of errors that went unrecognised by subjects, 56% were during Stroop No-gos. The level of Unaware errors is consistent with Rabbitt's (2002) data on levels of error awareness and correction when using a serial choice reaction time task. The speed of responses did not differ significantly between Go trials (569 ms), Aware errors (575 ms) and Unaware errors (617 ms) nor was there a significant difference between reaction times (RT) for Repeat errors (566 ms) and Stroop errors (581 ms). Post-error reaction times indicated two distinct patterns of behaviour, with significantly faster RT, or speeding-up, following an Aware error (pre-error trial RT minus post-error trial RT = −118 ms, $t_{12} = 3.54$, $P < 0.01$) and slowing down after Unaware errors (42 ms, $t_{12} = -2.62$, $P < 0.05$). It is important to note that the speeding of Post-Aware responses is confounded by subjects providing the alternate 'awareness' button press (consequently, they are not required to process the stimulus prior to responding), however, a similar pattern of significantly faster reaction times was observed for the first Go response following an Aware error (pre-Aware-error trial RT minus 2nd post-Aware-error trial RT = −57 ms, $t_{12} = 1.78$, $P < 0.10$). We have previously observed faster RT following errors with similar tasks, which we hypothesise is an adaptation to the task stimulus presentation ratio as subjects learn that No-go events are widely spaced. Further support for this hypothesis includes significantly faster RT following STOPS in the current study

(pre-STOP trial RT minus post-STOP trial = 66 ms, $t_{12} = 2.135$, $P = 0.054$).

The event-related functional analysis of Aware and Unaware errors identified thirteen activated areas that were used as regions-of-interest (ROIs) to compare activation for Aware and Unaware errors. Five clusters demonstrated significantly greater activation during Aware errors, located in the right (Brodmann's area 9: $x = 19$, $y = 41$, $z = 37$) and left prefrontal (BA 11/47: $x = -37$, $y = 36$, $z = -10$; and BA 47/38: $x = -40$, $y = 16$, $z = 18$) and bilateral inferior parietal cortices (BA 40: right: $x = 46$, $y = -48$, $z = 39$; and left: $x = -46$, $y = -50$, $z = 39$). Both the functionally defined rostral ACC ROI (BA 32: $x = 3$, $y = 40$, $z = 20$, $t(12) = 0.542$, $P = 0.59$) and a more dorsal ACC/pre-SMA ROI (BA 24/6/32: $x = 1$, $y = 14$, $z = 39$), $t(12) = -.260$, $P = 0.79$), taken from our meta-analysis of No-go errors (Hester et al., 2004), indicated equivalent levels of activation for Aware and Unaware errors (see Fig. 2). One region in the right prefrontal cortex (Brodmann's area 10: x: 34, y: 49, z: −2) showed significantly greater activation for unaware errors.

The Oddball condition, designed to estimate activation associated with altering the post-error button press, indicated significant activation (greater than zero) in only one of the Aware ROIs (Left Middle Temporal Gyrus, BA 21), confirming that the differences between Aware and Unaware errors did not result from this requirement.

Discussion

The results of the present study confirm a previous ERP finding that error-related ACC activation (as indexed by the error-related negativity) is not sufficient for explicit awareness of an error (Nieuwenhuis et al., 2001). Awareness of a response inhibition commission error in the current study was associated with bilateral prefrontal and parietal brain activation. Niewenhuis and colleagues (2001) found that error awareness was reflected in an ERP waveform known as the error positivity (Pe), which they hypothesised may arise from the same source as the P300 (or P3), because both are positive slow waves, occur 300 ms or later in the stimulus evoked ERP and are maximal at centro-parietal recording sites. The P300 is believed to have both anterior (e.g., prefrontal cortex) and posterior (e.g., parietal) cortical generators (Soltani and Knight, 2000), which may account for why the ERP signal averages to a centro-parietal site. The current results would appear to provide support for the Pe/P300 hypothesis, given that the regions we found to be associated with explicit error awareness are known to be the primary generators of the P300.

Our findings also demonstrate two distinct patterns of post-error behaviour: explicit recognition of an error that was associated with faster post-error response times, and possibly a form of implicit 'detection', where post-error responding showed a cautionary slowing but did not result in an explicit awareness. The significant ACC activation observed during both types of events is consistent with the hypothesis that the ACC detects conflict between competing responses (Botvinick et al., 2001; Carter et al., 1998). The conflict monitoring theory suggests that the ACC would be particularly active during No-go events, as they require significantly greater cognitive control in order to overcome the prepotent or more automatic Go response. However, the equivalent magnitude of activation for both types of errors would not support the ACC as being solely capable of exerting a causal influence on cognitive control in the form of post-error behavioural adjustments (Kerns et al., 2004; MacDonald et al., 2000).

Curiously, Gehring and Knight (2000) observed intact post-error slowing in prefrontally lesioned patients, leading Cohen and colleagues (2000) to suggest dissociable forms of control with post-error slowing reflecting general preparatory processes that are dictated by the locus coeruleus (LC) response to ACC detection of conflict. Our results could support such a model if it is the strength

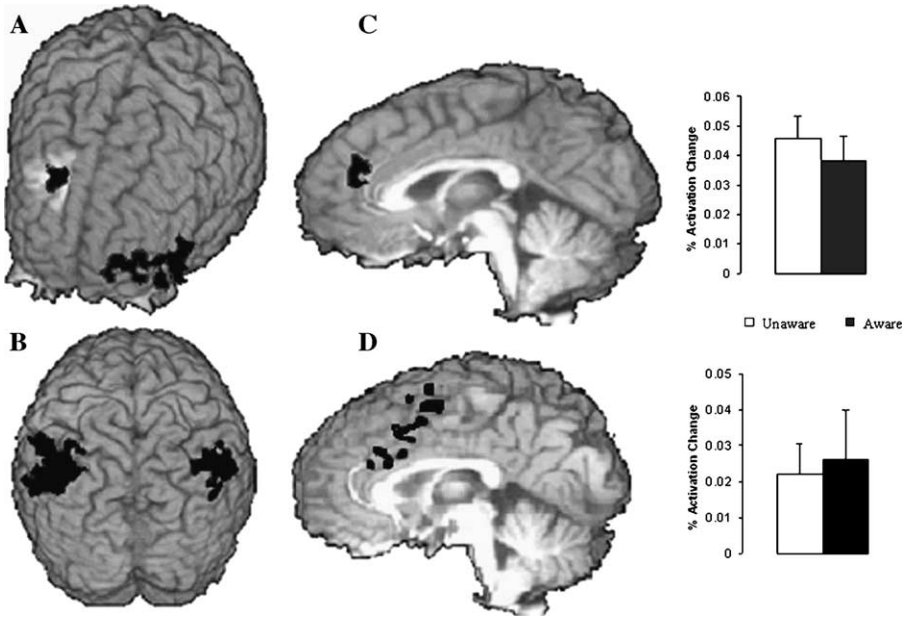

Fig. 2. Awareness of errors was associated with significantly higher activation in bilateral prefrontal and parietal ROIs (A and B). Equivalent levels of activation in both anterior (C) and dorsal cingulate ROIs (D—ROI taken from the analysis of No-go errors in 44 subjects in Hester et al., 2004) were seen for both Aware and Unaware errors.

of the LC, rather than ACC, response that dictates post-error processes, possibly via the LC's noradrenergic modulation of multiple subcortical and cortical areas (including prefrontal and parietal) (Nieuwenhuis et al., 2004; Robertson et al., 1998). However, it remains unclear what determines the strength of the LC's modulation.

These results appear consistent with Gehring and Knight's (2000) conclusions drawn from a clinical study in which cingulate activity from patients with lateral prefrontal damage no longer distinguished errors from correct responses. These authors argued for tighter coupling between the ACC and lateral PFC, with ACC monitoring events that must be checked against 'contextually appropriate stimulus–response mappings' maintained in the PFC for evaluation. In the present study, explicit recognition and correction of errors were associated with greater bilateral activity in both the lateral prefrontal and inferior parietal regions. In this regard, the ACC activity may be necessary for the detection of errors but is not sufficient for either the conscious awareness of errors or post-error adjustment of behaviour. Consequently, ACC impairment in clinical groups may still be relevant to the error processing deficits of those groups.

Theories attempting to explain error-related neural activity have not suggested that the detection of conflict (Botvinick et al., 2001; Carter et al., 1998), or detection of errors (Holroyd and Coles, 2002; Nieuwenhuis et al., 2004), necessarily infers awareness of this process. For example, an alternative explanation of the current results is that the error-related ACC activity represented the 'neural' detection of an error, which triggers the unconscious adjustment of behaviour, namely post-error slowing of responses seen previously (Garavan et al., 2002; Gehring et al., 1993; Kerns et al., 2004) and for Unaware errors here. The nature of this post-error slowing is of interest as no study to date has shown a relationship between neural activity during an error and reaction times for trials other than that immediately following an error. The dramatic changes in response times for the trial immediately following an error may simply be the result of an increase, albeit delayed, in cognitive control for an error that overflows onto the next trial. Data from Smith and Brewer (1995) suggest that, for young people, there is a significant slowing on the trial immediately following an error, but that for the second, third, and up to eight trials following an error, response times return to the mean reaction time. That post-error RT has returned to 'baseline' by the second trial after an error may indeed be adaptive (depending on the proportion of errors committed at this RT), however, this type of change and the significant slowing on the trial immediately following an error may be mediated by different mechanisms, which may or may not require conscious control or detection of the error.

It may be possible to distinguish a process that is limited to detecting phasic requirements for increased cognitive control that does not necessarily influence long-term strategic adaptations of behaviour and could potentially be achieved without the requirement for conscious awareness. For example, Rabbitt's (2002) study indicated that, while conscious recognition of errors, measured either as a post-error 'recognition' response or delayed probing of past errors, benefits from extended response stimulus interval durations (asymptoting at around 800 ms RSI), immediate correction occurred within 20 ms of a false response being made. Rabbitt concluded that, while the automatic correction of errors can be completed before being interrupted by a new signal within 150 ms, the deliberate selection of an 'error recognition' response and the formation of an 'error memory trace' where the error can be recalled at a later time take more post-response processing time. The absence of post-error slowing following Aware errors may therefore have been due to a masking effect, where the implementation of a conscious strategy (based on knowledge of the trial sequence) overrode the regular increase in post-error cognitive control. It is important to note that the pattern of functional activation following an Aware error is assumed to be related to processes required for awareness of an error. Given the limited temporal resolution of fMRI, this particular pattern of activation is also likely to include activation associated with the control processes that lead to subsequent performance adjustments. The neural mechanisms responsible for such performance adjustments remain relatively uncharacterised, though the left prefrontal cortex has been implicated in this phenomenon (for a review of this, see Ridderinkhof et al., 2004).

The present results, while in some regards striking in that they reveal that a specific brain structure, the ACC, may know more about our ongoing performance than we ourselves are aware of, leave us to query why errors are sometimes accompanied by lateral prefrontal–parietal activity, changes in post-error response strategies and error awareness, and sometimes not. The effect does not appear to result from 'missing' the inherent conflict of No-go trials, given the significant ACC activation over and above that for Go trials. Previous studies using degraded or subliminal stimuli suggest that the level of ACC activity is sensitive to conflict only when it can be consciously detected (Dehaene et al., 2001, 2003; Stephan et al., 2002). Mayr (2004) has recently suggested that Dehaene's results do not rule out the possibility that larger unconscious conflict effects could produce ACC-related activity, with the current results appearing to offer some support for this argument.

Recent contributions to the error literature have attempted to integrate the conflict hypothesis into a theory that encompasses the role of performance monitoring in reinforcement learning. Therefore, ACC activity might not reflect the detection of errors or conflict per se, but instead an evaluation process that predicts error likelihood for a particular stimulus type (Brown and Braver, 2005) or the absence of an anticipated reward (Nieuwenhuis et al., 2004; Ridderinkhof et al., 2004). We speculate that such an evaluation process relies on 'contextually appropriate stimulus–response mappings', which serve a proactive role in setting a context in which ACC activity prompts evaluation. That is, if the subject is in an attentive state where the appropriate response mappings are highly activated, then a context is set for phasic trial-related ACC activity to initiate a cascade of events in which the trial's response is evaluated and conscious post-error adaptation of behaviour results. Conversely, if the stimulus–response mappings are relatively underactivated at the point of encountering a relevant trial, then the evaluation signal reflected in ACC activity may not be sufficient to trigger awareness of an error or strategic adaptation of behaviour. It is reasonable to expect, and potentially advantageous for success, that during performance of a complex task our attention to a particular task rules will fluctuate. While it appears the ACC is proficient in detecting violations of predicted outcomes, momentary inattention to task demands might prevent the unconscious detection of an error resulting in conscious awareness of failure. Current evidence suggests that subjects who are prone to inattentiveness, indexed using a personality scale (Hester et al., 2004), have a diminished ACC response to errors, while on a trial by trial basis, subjects may demonstrate a diminished level of ACC or left

prefrontal activity on the trial(s) prior to a performance error (Ridderinkhof et al., 2003). Further studies assessing brain states that both precede and follow errors may illuminate these dynamics.

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