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Greater Activation of the “Default” Brain Regions Predicts Stop Signal Errors

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Abstract

Previous studies have provided evidence for a role of the medial cortical brain regions in error processing and post-error behavioral adjustment. However, little is known about the neural processes that *precede* errors. Here in an fMRI study we employ a stop signal task to elicit errors approximately half of the time despite constant behavioral adjustment of the observers (n=40). By comparing go trials preceding a stop error and those preceding a stop success, we showed that (at $p < 0.05$, corrected for multiple comparisons) the activation of midline brain regions including bilateral precuneus and posterior cingulate cortices, perigenual anterior cingulate cortices and transverse frontopolar gyri precedes errors during the stop signal task. Receiver operating characteristic (ROC) analysis based on the signal detection theory showed that the activity in these three regions predicts errors with an accuracy between 0.81 and 0.85 (area under the ROC curve). Broadly supporting the hypothesis that deactivation of the default mode circuitry is associated with mental effort in a cognitive task, the current results further indicate that greater activity of these brain regions can precede performance errors.

Keywords

attention; attentional lapse; prefrontal; neuroimaging

Introduction

The detection and processing of errors are critical to behavioral adaptation and skill acquisition. Previous imaging studies have identified the neural correlates of error detection and processing (Ullsperger and von Cramon, 2004; van Veen and Carter, 2002). For instance, commission errors during a go/no-go task evoked extensive activation in the rostral anterior cingulate cortex (ACC, Kiehl et al., 2000). The dorsal ACC responds both to an internal error signal generated by an endogenous response and to an external error signal supplied by the environment (Holroyd et al., 2004). A more recent fMRI study showed that activation of a region in the dorsal ACC is associated with learned prediction of error likelihood during a stop signal task (Brown and Braver, 2006). By comparing “go” trials with high and low probability of stop errors, these investigators demonstrated that the dorsal ACC and the pre-supplementary motor area learn to signal the error likelihood. Overall, these studies have indicated an important role

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of the medial cortical regions in monitoring performance during cognitive performance (Matsumoto and Tanaka, 2004; Ridderinkhof et al., 2004; Rushworth et al., 2004; Schall et al., 2002).

Little is known, however, whether there is a discernible pattern of brain activation that precedes performance errors, when observers do not know that errors are imminent, as in the aforementioned study of Brown and Braver, where participants learned to have advanced knowledge about the likelihood of errors. In other words, does the brain respond differently prior to the occurrence of an error when observers are not engaged in attentional monitoring of errors? Can we identify a neural signature that predicts errors?

To address this question, we employed a tracking stop signal task (SST) that elicited errors approximately half of the time despite constant behavioral adjustment of the observers. Errors can arise during the SST because of deficient response inhibition (inability to stop at the stop signal) or decreased attentional monitoring of the stop signal as when, for instance, responding to the go signal, assuming that no stop signal will show (Li et al., 2006). Thus, we identified in this latter study the anterior pre-supplementary motor area and bilateral middle and inferior frontal cortices, respectively, as mediating these two aspects of stop signal performance (Li et al., 2006). Lesser activation of these brain regions *at* the stop trials results in prolonged stop signal reaction time and stop errors. Another cognitive component that is temporally more extended and can influence stop signal performance relates to general vigilance or sustained attention. Previous studies have provided extensive evidence for an association between the activities in many midline brain regions – the so-called “default” brain circuitry – and performance in cognitive tasks (Greicius et al., 2003; Greicius and Menon, 2004; Raichle et al., 2001; Shulman et al., 1997; Tomasi et al., 2006). This brain circuitry shows greater activity when one is in an awake, relaxed state, as compared to when one is engaged in mental effort and information processing. In particular, in a recent study in which participants were to identify local versus global feature, greater activity of this circuitry is associated with performance lapses in this attention task (Weissman et al., 2006).

On the basis of these earlier studies, we examined whether neural processes that precede stop trials could influence stop signal performance. Thus, by comparing go trials preceding stop successes and stop errors, we examined whether regional brain activations could predict the occurrence of errors with reasonable accuracy. We broadly hypothesize that greater regional activity in regions within the default brain circuitry may precede stop errors, as compared to stop successes.

Materials and Methods

Subjects and behavioral task

Forty healthy adults (20 males, 22–42 years of age, all right-handed and using their right hand to respond, including the 24 subjects we reported in Li et al., 2006) were paid to participate in the study. Subjects were recruited in conjunction with other ongoing projects in the Department of Psychiatry. All subjects participated in a formal assessment with the Diagnostic and Statistical Manual IV (American Psychiatric Association, 1994) to rule out psychiatric illnesses. Urine toxicology tests were performed to rule out use of illicit substances. All participants were free of medical including neurological illnesses. Individuals who were on psychotropic medications were not eligible for the study. The majority of these subjects were not admitted for inpatient stay, so no physical examination was administered, nor was IQ or other neuropsychological functioning assessed. All subjects signed a written consent after details of the study were explained, in accordance to institute guidelines and procedures approved by the Yale Human Investigation Committee.

The behavioral task ran from a commercial software “Presentation” (NeuroBehavioral Systems; <http://www.neurobs.com/>). Visual stimuli were front projected to a screen situated in front of the scanner, and manual response via button press was recorded with a fiber-optic button box (Current Designs, Philadelphia, PA). We employed a simple reaction time task in this stop-signal paradigm (Li et al., 2006; Logan and Cowan, 1984; >Fig. 1a). There were two trial types: “go” and “stop,” randomly intermixed. A small dot appeared on the screen to engage attention and eye fixation at the beginning of a go trial. After a randomized time interval (fore-period) anywhere between 1 and 5 sec, the dot turned into a circle, which subtended approximately 2° of visual angle. The circle served as an imperative stimulus and the subjects were instructed to quickly press a button at the “go” signal but not before. The circle vanished at button press or after 1 sec had elapsed, whichever came first, and the trial terminated. A premature button press prior to the appearance of the circle also terminated the trial. Three quarters of all trials were go trials. The remaining one quarter were stop trials. In a stop trial, an additional “X,” the “stop” signal, appeared after and replaced the go signal. The subjects were told to withhold button press upon seeing the stop signal. Likewise, a trial terminated at button press or when 1 sec had elapsed since the appearance of the stop signal. Clearly it would be easier for the subject to withhold the response if the stop signal appeared immediately or early after the go signal, and the reverse applied if the time interval between the stop and the go signals (or the stop-signal delay, SSD) was extended. The SSD started at 200 msec and varied from one stop trial to the next according to a staircase procedure: if the subject succeeded in withholding the response, the SSD increased by 64 msec; conversely, if they failed, SSD decreased by 64 msec (Levitt, 1970). There was an inter-trial-interval of 2 sec. Subjects were instructed to respond to the go signal quickly while keeping in mind that a stop signal could come up in a small number of trials. Prior to the fMRI study each subject had a practice session outside the scanner. In the scanner each subject completed four 10-min runs of the task with the SSD updated manually across runs. Depending on the actual stimulus timing (trial varied in fore-period duration) and speed of response, the total number of trials varied slightly across subjects in an experiment. With the staircase procedure we anticipated that the subjects succeeded in withholding their response in approximately half of the stop trials.

Imaging protocol

We employed a 3T scanner (Siemens Trio) and a standard circularly-polarized volume coil for the current study. Conventional T₁-weighted spin echo sagittal anatomical images were acquired for slice localization. Anatomical images of the functional slice locations were next obtained with spin echo imaging in the axial plane parallel to the AC-PC line with TR = 300 msec, TE = 2.5 msec, bandwidth = 300 Hz/pixel, flip angle = 60°, field of view = 220 × 220 mm, matrix = 256 × 256, 32 slices with slice thickness = 4mm and no gap. Functional, blood oxygenation level dependent (BOLD) signals were then acquired with a single-shot gradient echo echoplanar imaging (EPI) sequence. Thirty-two axial slices parallel to the AC-PC line covering the whole brain were acquired with TR = 2,000 msec, TE = 25 msec, bandwidth = 2004 Hz/pixel, flip angle = 85°, field of view = 220 × 220 mm, matrix = 64 × 64, 32 slices with slice thickness = 4mm and no gap. Three hundred images were acquired in each run for a total of 4 runs.

Data analysis and statistics

Data were analyzed with Statistical Parametric Mapping version 2 (SPM2, Wellcome Department of Imaging Neuroscience, University College London, U.K.). Images from the first five TRs at the beginning of each trial were discarded to enable the signal to achieve steady-state equilibrium between RF pulsing and relaxation. Images of each individual subject were first corrected for slice timing and realigned (motion-corrected). A mean functional image volume was constructed for each subject for each run from the realigned image volumes. These mean images were normalized to an MNI (Montreal Neurological Institute) EPI template with

affine registration followed by nonlinear transformation (Ashburner and Friston, 1999; Friston et al., 1995a). The normalization parameters determined for the mean functional volume were then applied to the corresponding functional image volumes for each subject. Finally, images were smoothed with a Gaussian kernel of 10 mm at Full Width at Half Maximum. The data were high-pass filtered (1/128 Hz cutoff) to remove low-frequency signal drifts.

Four main types of trial outcome were first distinguished: go success (G), go error (F), stop success (SS), and stop error (SE) trial (Fig. 1a). For the evaluation of “pre-stop” processes, G trials were further divided into those that preceded a G (pre-G), SS (pre-SS), and SE (pre-SE) trial (Fig. 1b). A statistical analytical design was constructed for each individual subject, using the general linear model (GLM) with the onsets of go signal in each of these trial types convolved with a canonical hemodynamic response function (HRF) and with the temporal derivative of the canonical HRF and entered as regressors in the model (Friston et al., 1995b). Realignment parameters in all 6 dimensions were also entered in the model. Serial autocorrelation of the time series caused by aliased cardiovascular and respiratory effects violated the GLM assumption of the independence of the error term and was corrected by a first-degree autoregressive or AR(1) model (Della-Maggiore et al., 2002; Friston et al., 2000). The GLM estimated the component of variance that could be explained by each of the regressors.

In the first-level analysis, we constructed for each individual subject one statistical contrasts: pre-SS vs. pre-SE. The *con* or contrast (difference in β) images of the first-level analysis were then used for the second-level group statistics (random effect analysis; Penny and Holmes, 2004). Brain regions were identified using an atlas (Mai et al., 2003). In region of interest (ROI) analysis, we used MarsBaR (Brett et al., 2002; <http://marsbar.sourceforge.net/>) to derive for each individual subject the % signal change and the effect size of activity change for the ROIs. All voxel activations are presented in MNI coordinates.

Receiving operating characteristic (ROC) analysis of the neural predictability of stop errors

Based on the theory of signal detection, the ROC analysis provides a useful tool to evaluate the accuracy with which neural activities predict errors (Macmillan and Creelman, 1991). The ROC analysis required variability in performance. Our tracking stop signal task (SST) ensured that participants succeeded in approximately half of the stop trials. However, each participant completed four sessions of the SST and performance varied across the four sessions ($50.2 \pm 10.2\%$; mean $\pm$ s.d.; $n=160$). Thus, we examined across all participants how well activity in each of the ROIs differentiated performance in a session with an SE rate one standard deviation (s.d.) above the mean (i.e., SE rate $>60.4\%$; $n=39$) from a session with an SE rate one s.d. below the mean (i.e., SE rate $<40.0\%$; $n=15$). The ROC curve was constructed by incrementally varying the threshold on the effect size of activity change and computing the percentage of sessions correctly (sensitivity) and incorrectly (bias) categorized as “SE.” Area under the ROC curve was estimated after the curve was fitted with a piecewise cubic hermite interpolating polynomial (PCHIP; Epperson, 2001; Heath, 2002). Specifically, piecewise interpolation was employed to avoid oscillatory behaviors as may occur when a single polynomial interpolant was used. A hermite cubic rather than spline interpolant was used to allow for the flexibility in preserving the monotonicity of the ROC function.

Results

General behavioral performance

Behavioral results are summarized in Table 1a. Stop signal reaction time (SSRT), computed on the basis of the horse race model, is included in the table for completeness (Logan, 1984). Table 1b lists percentages of go and stop success, which did not differ across the four sessions

($F_{3,117}=2.210$, $p=0.112$, for go success %; $F_{3,117}=1.319$, $p=0.272$, for stop success %, repeated measures ANOVA).

Neural activity preceding SE vs. SS trials

Unless otherwise noted, we imposed a threshold on our results by using a $p<0.05$, corrected for family-wise errors (FWE) in multiple comparisons for the whole brain (i.e., $T<4.91$). Compared to pre-SS trials, the pre-SE trials showed greater activation in bilateral posterior cingulate cortices and precuneus (3 activation peaks 8mm apart: $x=-16$, $y=-60$, $z=32$, voxel $Z=5.28$; $x=-12$, $y=-56$, $z=40$, voxel $Z=4.94$; $x=20$, $y=-60$, $z=24$, voxel $Z=4.79$; bilateral Brodmann area or BA 31 and 7, total volume=6,592mm³), perigenual anterior cingulate cortices ($x=4$, $y=32$, $z=4$, voxel $Z=4.93$, bilateral BA 24, total volume=1,408mm³), and transverse frontopolar gyri ($x=4$, $y=52$, $z=24$, voxel $Z=4.47$, bilateral BA 9, total volume=768mm³, Fig. 2). The activity of these 3 brain regions were highly correlated across subjects ($0.59<R_s<0.66$, $p<0.0001$, pair-wise Pearson regressions).

The time course plots in Figure 2 suggest that pre-SE and pre-G trials show a similar pattern of activation, as compared to pre-SS trials, in the two frontal regions. To confirm this impression, we contrasted pre-SE with pre-G trials and observed that no regional brain activations differentiated these two trial types even at a lower threshold of $p<0.05$, corrected for false discovery rate (Genovese et al., 2002). On the other hand, pre-G trials showed greater activation in the posterior cingulate cortex (PCC, $x=-4$, $y=-52$, $z=28$, voxel $Z=4.45$, 128mm³), compared to pre-SS trials. Thus, overall, pre-G and pre-SE trials resembled while differing from the pre-SS trials in brain activity, particularly in the PCC.

We further examined whether these results could be validated in an independent sample of healthy individuals ($n=12$; 6 men and between 25 to 41 years of age) who were recruited for another ongoing study and performed the identical stop signal task under fMRI. We focused on the afore-described three brain areas as the regions of interest (ROI). The results showed greater activation in the posterior cingulate/precuneus ($x=-8$, $y=-60$, $z=36$, voxel $Z=3.74$, 384 mm³) and the perigenual anterior cingulate ($x=0$, $y=32$, $z=2$, voxel $Z=3.24$, 256 mm³), at $p<0.001$, uncorrected. The transverse frontopolar gyrus ($x=2$, $y=50$, $z=18$, voxel $Z=2.58$, 128 mm³), also showed greater activation for this contrast at a lower threshold ($p<0.005$, uncorrected).

We also examined if other brain regions in the default brain circuitry showed differential activity preceding SE vs. SS trials, at a more liberal statistical threshold. At a $p<0.0005$, uncorrected (i.e., $T<3.56$) and 5 voxels in the extent of activation, additional small and spotty activations were observed in the right temporal lobe, left inferior frontal cortex, and left middle to superior frontal cortices (Fig. 3). Notably, the paracentral lobules, dorsal medial frontal cortices, and inferior parietal regions including the angular gyri did not show greater activity in such a contrast (Gusnard and Raichle, 2001).

Potential effects of demographic variables and inter-subject variation in performance

Our subjects varied in age and gender so we examined whether these demographic variables could have an effect on the results. To this end we examined in a linear regression for the whole brain for age-correlated regional brain activation; the results showed no clusters with greater activation during pre-SE, as compared to pre-SS trials, at $p<0.01$, uncorrected and 5 voxels in extent. In a 2-sample t test, we compared men and women for the contrast pre-SE>pre-SS and the results are negative at $p<0.01$, uncorrected and 5 voxels in extent. We also performed ROI analyses for correlation between activity and age with linear regression and for gender effect with 2-sample t test. The results of these analyses were all negative for the three ROI's (all $P_s>0.27$ for age correlation and gender effect).

Individuals varied in stop signal performance. In particular, subjects varied in their go trial RT (and thus in the critical SSD) during the tracking procedure (go trial RT is correlated with critical SSD across subjects; Pearson $R=0.968$, $p<0.0001$). Therefore, we examined in exploratory analyses whether regional brain activation varied with critical SSD across subjects. The result showed that the effect size of pre-SE>pre-SS in the perigenual anterior cingulate correlated positively with SSD across subjects (Pearson $R=0.427$, $p<0.006$). No such correlation was found for the posterior cingulate cortex/precuneus ($p=0.055$) or the transverse frontopolar gyrus ($p=0.818$).

Predictability of errors

To examine the accuracy with which these regional brain activations could predict SE vs. SS, we focus on the three ROIs identified with a $p<0.05$, corrected for FWE. The results of receiver operating characteristic analysis showed that the activity in posterior cingulate cortex (PCC), rostral anterior cingulate cortex (rACC), and transverse frontopolar (TFP) gyrus each predicted stop errors with an area under the ROC curve of 0.85, 0.81 and 0.83 (Fig. 4).

How early can these brain activations predict stop errors – an exploratory analysis?

The inter-(go) onset- interval averaged approximately 5.75 sec in the current behavioral task; thus, these results suggest that a differential pattern of activity in these brain regions could dictate behavioral performance more than 5 sec later during the stop signal task. An interesting question is how early could these regional brain activities be observed differentiating an SE from an SS? To answer this question, we constructed a second SPM, by sub-categorizing go trials on the basis of their “second-order” structure, so that we could examine whether go (G) trials preceding the stop trials by an average of two inter-onset-intervals (11.5 sec) were associated with a similar pattern of brain activation. The results showed that no brain regions activate differently between pre-G-SE and pre-G-SS go trials, even at a threshold of $p=0.01$, uncorrected, and 5 voxels in extent of activation. ROI analyses involving the PCC/precuneus, ACC and FPC also similarly yielded negative results at $p=0.05$, uncorrected. Thus, the error-predicting pattern of midline brain activation appears no earlier than 11.5 seconds prior to the error.

Discussion

The major finding of the current study is that activation or decreased deactivation of bilateral posterior cingulate cortex (PCC), precuneus, perigenual anterior cingulate cortex (ACC) and frontopolar cortex (FPC) precedes stop errors during the stop signal task. This differential pattern of activity occurs at a time when our observers do not know the imminence of an error or, in fact, of a stop trial. This psychological dimension critically differentiates the current findings from those of Brown and Braver, where participants had learned to predict the error likelihood. These regions all reside along the midline of the brain and are part of the default-mode brain circuitry (Raichle et al., 2001; Shulman et al., 1997). The current results are thus consistent with previous studies associating deactivation of this network of brain regions with goal-directed behaviors and/or mental effort during a cognitive task (Greicius et al., 2003; Greicius and Menon, 2004; Raichle et al., 2001; Shulman et al., 1997; Tomasi et al., 2006).

These results accord particularly well with the aforementioned study showing that attentional lapses are associated with increased “default-mode” network activity (Weissman et al., 2006). In a global/local selective-attention task, in which participants identified either the large, global letter or the small, local letters of a hierarchically organized visual object, longer reaction times were associated with increased target-related activity in several regions of the default-mode network, including the PCC, the precuneus, and the middle temporal gyrus. The latter results suggested that less effective suspension of task-irrelevant mental processes could lead

to momentary lapses in attention during a cognitive task (Weissman et al., 2006). Thus, among the brain regions in the default network, the PCC/precuneus appears to play a critical role in determining cognitive performance. On the other hand, the default circuitry is probably involved in a wide range of cognitive functions; while some studies suggested that deactivation of the default brain circuitry appears to be invariant to specific behavioral tasks in which observers are involved (Raichle et al., 2001; Tomasi et al., 2006), other studies have provided evidence for functional specificity, such as the medial prefrontal cortex in self-referential mental activity, the ventral medial prefrontal cortex in mediating physiological arousal, the right insula during stimulus-independent thoughts, and the right temporal parietal junction during visual search (Gusnard et al., 2001; Mason et al., 2007; Nagai et al., 2004; Shulman et al., In Press). Further studies are thus warranted to examine how these brain regions are involved differently when we are engaged in varying task conditions and, indeed, in different neurological conditions (Greicius et al., 2004; Greicius et al., In press; Kennedy et al., 2006; Laufs et al., In press; Rombouts et al., 2005).

In the current study, the activity of the three brain regions was highly correlated across subjects, suggesting that they activate in a concerted manner during events prior to the occurrence of an error, consistent with the hypothesis that these brain regions are inter-connected forming a network (Damoiseaux et al., 2006; Greicius et al., 2003; Hampson et al., 2006; Laufs et al., 2003). On the other hand, other clues suggest functional differentiation between these brain regions. For instance, activity of perigenual ACC but not the other two regions is significantly (though only weakly) correlated with critical SSD across subjects. Since a long SSD (and hence a slow go trial RT) is associated with a more conservative response strategy, this result potentially suggest an important variation in performance and neural activation across subjects who apparently follow the same psychophysical procedure. For instance, ACC plays a crucial role in performance monitoring (Carter et al., 1998; Ito et al., 2003; Van Veen and Carter, 2002). Thus, is it possible that the ACC is involved in the conscious aspect of attentional monitoring, whereas the posterior cingulate cortex (PCC)/precuneus is engaged without substantial self-awareness of the participants, during the stop signal task? This interpretation seems also consistent with the finding that the PCC/precuneus but not the ACC or transverse frontopolar gyrus showed significant greater activation during preG>pre-SS. Thus, the PCC/precuneus appears to be a brain region mediating general vigilance, a baseline mental state upon which other cognitive variables are superimposed to dictate behavioral performance (Lawrence et al., 2003; Mesulam, 1981). This contrast between ACC and PCC in attentional engagement warrants further studies (Vogt et al., 1992).

Although it is premature to directly compare fMRI and event-related potential (ERP) work, the current results are reminiscent of an earlier ERP study showing enhanced positivity at a frontal locale on error-preceding trials, compared to correct-preceding trials, during a flanker task (Ridderinkhof et al., 2003). It was hypothesized that this error-preceding positivity (EPP) was a neural correlate of deficient monitoring prior to actual execution of an error. This result was replicated and extended in a later study, which ruled out the effect of stimulus-related processing and confirmed the temporal specificity of this finding to “error-1,” but not “error-2” or “error+1” trials (Hajcak et al., 2005). Thus, one is tempted to speculate that the EPP observed in these earlier studies may be related to the greater error-predicting cingulate/frontopolar activity observed in the current work, an association that can only be ascertained by combining fMRI and ERP in an experiment.

Since pre-SE and pre-SS trials are both go trials and thus presumably engaging the same visuomotor processes, it is intriguing that by contrasting these two trials, one could isolate regional brain activities that precede the occurrence of a performance error. Our analysis of the second-order trial structure showed that the error-predicting pattern of midline brain activity appears no earlier than 11.5 seconds prior to the occurrence of an error, a result that would be

of relevance to the practical implications of this finding. For example, if this error-predicting activity could be garnered to warn a pilot, then he/she would have 5.75 seconds but probably not reliably more time to act in order to avert an impending, perhaps catastrophic, mistake.

The activity of these brain regions predicts stop signal error less than perfectly. These regional brain activities predict errors with an accuracy between 0.8 and 0.85, indicating that greater activation in these regions is associated with approximately a 10-fold increase in the odds that observers are “committed” to a mistake (Boyko and Alderman, 1990; Lachenbruch, 1997). An important factor needs to be considered to account for this limited accuracy. Because of the weak BOLD signal associated with single trials and the requirement to combine multiple trials (grouped according to each distinct event, e.g., SE, SS, etc) in statistical modeling, the regional brain activities we employed for the receiver operating characteristic (ROC) analysis were not associated categorically with a stop success or stop error. Rather, they represented a continuous measure of the likelihood of stop success/error. The ROC analysis thus came with an intrinsic limitation on how performance could be accurately predicted and should thus be deemed “descriptive.” An additional issue to consider is that we did not include a “rest” or “baseline” condition in the behavioral task. We thus do not know whether these greater regional brain activations represent differential activation or deactivation than the baseline condition (Northoff and Bermpohl, 2004).

In conclusion, we have identified a distinct pattern of neural activities that precede errors during the stop signal task. While previous findings of medial cortical activations during error processing mostly reflect attentional monitoring for error, the current results appear to represent a neural signature that predicts error.

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(a) GO trials: Success **G**; Error **F**

(b) An example sequence of trials:

Li et al., Figure 1

FIGURE 1.

(a) stop signal paradigm. In “go” trials (75%) observers responded to the go signal (a circle) and in “stop” trials (25%) they had to withhold the response when they saw the stop signal (an X). In both trials the go signal appeared after a randomized time interval between 1 to 5 sec (the fore-period or FP, uniform distribution) following the appearance of the fixation point. The stop signal followed the go signal by a time delay – the stop signal delay (SSD). The SSD was updated according to a staircase procedure, whereby it increased and decreased by 64 msec following a stop success and stop error trial, respectively. We distinguished go success (G, $97.1 \pm 2.7\%$, mean $\pm$ s.d.) and go error (F, 2.9%), and stop success (SS, $50.3 \pm 2.6\%$) and stop error (SE, 49.7%) trials during the task. (b) Go successes were further distinguished by their subsequent trial; thus G trials followed by a G, SS, and SE trial were indicated by pre-G, pre-SS, and pre-SE trials, respectively.

FIGURE 2.

Brain regions showing greater activation during pre-SE than pre-SS trials at a $p < 0.05$, corrected for family-wise errors of multiple comparisons, and 5 voxels in the extent of activation. On the right, BOLD signals are overlaid on sagittal slices (from $x = -12\text{mm}$ to $+12\text{mm}$) of a smoothed structural image. Activated regions include the posterior cingulate cortex/precuneus (a), a subregion in the rostral anterior cingulate cortex (b), and the transverse frontopolar gyrus (c). Color bar represents voxel T value. On the left, the time course of % signal change is plotted for the three regions. The red, blue, and black curve each represents pre-SE, pre-SS, and pre-G trials, with overlapping vertical bars being standard deviations.

FIGURE 3.

Brain regions showing greater activation during pre-SE than pre-SS trials at a $p < 0.0005$, uncorrected, and 5 voxels in the extent of activation. BOLD signals are overlaid on axial slices (from $z = -35\text{mm}$ to $+55\text{mm}$) of a smoothed structural image, with adjacent sections 5mm apart. Additional small clusters are observed in the right temporal lobe, left inferior frontal cortex and left middle to superior frontal cortices. Color bar represents voxel T value.

FIGURE 4.

Receiver operating characteristic (ROC) curves illustrate the sensitivity and specificity of the posterior cingulate cortex (PCC), rostral anterior cingulate cortex (rACC) and the transverse frontopolar (TFP) gyrus activity in predicting performance during each stop signal session. Each region of interest is highlighted in blue in a coronal and sagittal section. Each red dot represents the result obtained on the basis of one threshold to categorize a session as stop success or stop error. As the threshold decreases, the sensitivity increases as more sessions were correctly categorized as SE, but the specificity decreases (or bias increases) as more sessions were incorrectly categorized as SE. The black curve indicates the fitted ROC curve.

Table 1a

General performance in the stop signal task

	go RT (msec)	%go	%stop	SSRT (msec)	critical SSD (msec)
Group 1 (n=40)	547 ± 115	97.1 ± 2.7	50.3 ± 2.6	216 ± 32	332 ± 124
Group 2 (n=12)	605 ± 94	96.3 ± 1.3	51.2 ± 2.5	197 ± 44	408 ± 103
P value	0.11	0.32	0.30	0.41	0.06

Table 1b

Variation of %go and %stop across sessions (Group 1, n=40)

	Session 1	Session 2	Session 3	Session 4
Go %	98.4 ± 3.1%	97.4 ± 3.6%	96.5 ± 4.6%	96.1 ± 5.1%
Stop %	50.1 ± 6.3%	50.0 ± 4.7%	50.4 ± 7.5%	50.6 ± 6.0%

Note: %go and %stop: percentage of successful go and stop trials; SSRT: stop-signal reaction time; all numbers are mean ± standard deviation; P value based on 2-tailed two-sample t test.

Table 2

Regional brain activation: pre-SE > pre-SS

cluster size (voxels)	voxel Z value	MNI coordinate (mm)			Side	Identified region and approximate Brodmann area (BA)
		x	y	z		
103	5.28	-16	-60	32	L	Posterior cingulate G/Precuneus, BA 31
	4.94	-12	-56	40	L/R	Precuneus, BA 7
	4.79	20	-60	24	R	Posterior cingulate G/Precuneus, BA 31/7
22	4.93	4	32	4	L/R	Perigenual anterior cingulate G, BA 24
12	4.47	4	52	24	L/R	Transverse frontopolar G, BA 9

Note: p<0.05, corrected for family-wise error, 1 voxel=64mm³; G: Gyrus