

**Performance-related activity in medial rostral prefrontal cortex
(area 10) during low-demand tasks**

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Running title: MEDIAL ROSTRAL PFC

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Acknowledgements

This work was supported by the Wellcome Trust (061171), ESRC (PTA-026-27-0317), and by MRC co-operative grant number G9900106.

ABSTRACT

Neuroimaging studies frequently observe relatively high activity in medial rostral prefrontal cortex (PFC) during rest or baseline conditions. Some accounts attribute this to the occurrence of unconstrained stimulus-independent and task-unrelated thought processes during baseline conditions. Here, we investigate the alternative possibility that medial rostral PFC supports attention towards the external environment during low-demand conditions. Participants performed a baseline simple RT task, along with three other tasks that differed in the requirement to attend to external stimuli versus stimulus-independent thought. Medial rostral PFC activation was observed both in the baseline task and in a condition requiring strong engagement with external stimuli, relative to two conditions with greater requirement for stimulus-independent thought. Importantly, activity in this region was associated with faster RTs in the baseline task, ruling out an explanation in terms of task-unrelated thought processes during this condition. Thus, at least under certain circumstances, medial rostral PFC appears to support attention towards the external environment, facilitating performance in situations that do not require extensive processing of experimental stimuli.

Periods of “rest”, where participants are not instructed to perform any particular task, and simple baseline tasks such as passive fixation of visual stimuli, have been associated with increased activity in certain brain regions relative to cognitive tasks requiring more extensive processing and manipulation of experimental stimuli. The location of these brain regions shows remarkable consistency across studies, despite the wide range of cognitive tasks investigated (involving such disparate domains as perceptual monitoring, visual attention, language and memory). These regions have therefore been hypothesized to participate in a “default mode of brain function” (Raichle et al., 2001), which is suspended during various attention-demanding, goal-directed activities. The structures implicated in this “default mode” are predominantly located along the medial wall, including the precuneus and posterior cingulate, as well as a large expanse of medial rostral prefrontal cortex (PFC) encompassing Brodmann Areas (BAs) 8,9,10 and 11 (Binder et al., 1999; Greicius, Krasnow, Reiss & Menon, 2003; Mazoyer et al., 2001; McKiernan, Kaufman, Kucera-Thompson & Binder, 2003; Shulman et al., 1997; Gusnard & Raichle, 2001; Gusnard et al., 2001).

Along with “low-demand tasks”, defined here as any task with minimal requirement to perform cognitive operations on experimental stimuli, neuroimaging studies have also implicated medial rostral PFC in a wide variety of tasks that may involve reflection on one’s own mental states. Examples of such tasks are those involving “mentalizing” (i.e. attributing mental states to others; Frith & Frith, 2003; see also Bird, Castelli, Malik, Frith & Husain, 2004); social cognition (Iacoboni et al., 2004); moral (Greene et al., 2001) and emotional (Damasio et al., 2000; Lane et al., 1997) decision making; judging one’s own character traits (Johnson et al., 2002); and evaluative

judgements (Zysset, Huber, Ferstl & von Cramon, 2002). Such neuroimaging findings have provoked the suggestion that the medial rostral PFC plays a general role in self-referential mental processes (Gusnard et al., 2001), and that the occurrence of unconstrained self-referential thought processes during baseline conditions is responsible for the relatively high level of medial rostral PFC activity during such conditions (McKiernan et al., 2003; Wicker, Ruby, Royet & Fonlupt, 2003).

According to this hypothesis, the activation that is observed in medial rostral PFC during baseline tasks is not related to any process that plays a functional role in accomplishing these tasks. Rather, this activation is attributed to thought processes which are both *task-unrelated*, which we define here as any cognitive process that does not help subjects to accomplish the instructed task, and *stimulus-independent*, which we define here as any cognitive process that is decoupled from information currently available in the sensory environment (for further discussion of these terms see Antrobus, 1968; Burgess, Simons, Dumontheil & Gilbert, 2005; Christoff, Ream & Gabrieli, 2004; Giambra, 1995; Gilbert, Frith & Burgess, 2005; McGuire et al., 1996; Smallwood, Obonsawin & Heim, 2003; Teasdale et al., 1995). For example, McKiernan et al. (2003, p.403) suggest that “as task demands increase, processing resources are increasingly diverted from ongoing, internal processes occurring at ‘rest’ to areas that are involved in the task”.

In the present study, we investigate an alternative explanation of medial rostral PFC activation in low-demand conditions. We suggest that medial rostral PFC may indeed play a functional role during baseline tasks, by promoting attentional engagement with the external environment during low-demand conditions. This possibility is

consistent with the results of several recent neuroimaging studies that have reported medial rostral PFC activation in tasks requiring strong attentional engagement with the external environment. For example, Small et al. (2003) found that activity in this region (along with posterior cingulate) was associated with the deployment of visual attention towards specific regions of space, in a spatial cueing paradigm (Posner, 1980). Janata et al. (2002) found that activity in medial rostral PFC varied systematically according to the musical key of a melody, in an auditory vigilance task. Burgess et al. (2003) found that activity in medial rostral PFC was greater in a variety of tasks while subjects performed those tasks alone, compared with when they performed those tasks whilst holding in mind a delayed intention. Recently, across three quite separate tasks, Gilbert, Frith, & Burgess (2005) consistently found greater activity in medial rostral PFC during task phases that required subjects to attend to externally-presented information, compared with phases where they attended to internally-generated information. Thus, contrary to the claim that medial rostral PFC is exclusively involved in stimulus-independent thought (e.g. Wicker et al., 2003), this region has been implicated in a variety of tasks involving attentional engagement with the external environment.

One potential way of clarifying the role of medial rostral PFC in baseline tasks is to investigate the relationship between activity in this region and fluctuations in behavioral performance. Insofar as this activity reflects task-unrelated and stimulus-independent processes, the occurrence of these processes (and hence level of medial rostral PFC activity) should correlate on a trial-by-trial basis with worse performance (e.g. slower RTs) in the baseline task, since subjects will be distracted from the task. Alternatively if medial rostral PFC activity reflects engagement with the external

environment, activity should correlate positively with performance in baseline tasks (e.g. trials with faster RTs). Unfortunately, there is currently little data with which to evaluate this question, because previous studies investigating baseline conditions have tended to use tasks with no response requirements (e.g. rest, passive fixation). Other studies that have investigated the relationship between activity in medial PFC and behavioral performance (e.g. Bunge, Ochsner, Desmond, Glover & Gabrieli, 2001; Laurienti et al., 2003) have typically investigated the relationship between individual differences in behavioral performance and individual differences in BOLD signal (i.e. by investigating whether subjects who show relatively large differences between two conditions in behavioral performance also show relatively large differences between those conditions in medial PFC BOLD signal). Such analyses may be difficult to interpret because the causes of between-subject variation are likely to be complex. In the present study, we took the alternative approach of investigating the relationship in each subject between trial-by-trial fluctuations in behavioral performance and trial-by-trial fluctuations in BOLD signal, within a single task (cf. West & Alain, 2000 for a related approach).

To test for brain-behavior relationships in baseline conditions, we employed a simple RT task as a baseline, in which subjects simply pressed a response button every time the screen flashed (with these events occurring at unpredictable times). The simple RT task is appropriate for two reasons. First, like other baseline tasks such as passive fixation (Shulman et al., 1997), this task does not require any cognitive processing of stimuli, only the detection of their occurrence, and therefore fits our definition of “low-demand” tasks as those with minimal requirements to perform cognitive operations on experimental stimuli. Second, in this task the stimulus, response and stimulus-response

mapping are identical on every trial, so fluctuations in performance can be attributed to variation in the subject's psychological state (e.g. the degree of attention towards the external environment), rather than variation in the difficulty of different types of trial.

The present study also investigated three other conditions, which differed in the requirement to attend to externally-presented versus internally-generated information. We reasoned as follows. If activity in medial rostral prefrontal cortex reflects the occurrence of stimulus-independent thoughts, this activity should be relatively high in conditions where subjects are instructed to ignore stimuli, compared with conditions involving attention towards external stimuli. Furthermore, if activity in medial rostral prefrontal cortex reflects the occurrence of task-unrelated thoughts, this activity should correlate with slower RTs in the baseline task, since it will reflect distraction from the task in hand. On the other hand, if activity in this region reflects engagement with the external environment during baseline conditions, this activity should be high in conditions requiring attention to externally-presented information, and should correlate with faster RTs in the baseline task.

Additionally, we sought in the present study to clarify the results from our previous study (Gilbert, Frith & Burgess, 2005) in which we investigated the neural bases of stimulus-oriented versus stimulus-independent thought. In this previous study, subjects performed three different tasks, each of which they could accomplish either by using externally-presented information (i.e. stimulus-oriented thought) or by doing the same task "in their heads". Consistently across the three tasks, we found that medial rostral PFC activity was greater in the phases involving stimulus-oriented versus stimulus-independent thought. However, these two types of condition differed in two potentially

dissociable ways. First, the stimulus-oriented phases, unlike the stimulus-independent phases, required the processing of sensory information. Second, the stimulus-independent phases, unlike the stimulus-oriented phases, required subjects to generate the task-relevant information themselves, since it was not available to them perceptually. In order to dissociate these two factors, the present study included an additional condition, which required subjects both to generate task-relevant information themselves, and also to process incoming sensory information. By comparing this condition against a stimulus-oriented condition, requiring strong engagement with the external environment but no self-generation of information, and a stimulus-independent condition, requiring the self-generation of information but no processing of incoming sensory information, we were able to investigate these two factors independently of one another.

METHOD

Subjects

There were 14 healthy right-handed participants, aged 22-36 (mean: 26; nine female). All provided written informed consent before taking part.

Tasks

Two tasks (*Numbers* and *Letters*) were performed in separate scanning sessions. Each task consisted of four separate conditions. In all conditions stimuli appeared in a central viewing area approximately 1.5° wide and 3° tall. A continuously updated stream of stimuli passed through this viewing area, moving smoothly from the bottom to the top in

the manner of film credits. At any one time, up to three stimuli were visible (see Figure 1). Throughout all conditions, the stimuli were degraded by superimposing 200 small squares over the stimulus-viewing area, the positions of which constantly changed with each screen-refresh (refresh rate: 60 Hz).

[Figure 1 about here]

A) Baseline condition: Stimuli consisted of repeated presentations of the number “0” (*Numbers* task) or the letter “A” (*Letters* task). Intermittently, the entire screen was illuminated for 100 ms. Subjects were asked to press a button with their index finger as soon as this occurred. The time from one target to the next was sampled from a uniform distribution, ranging from 67% to 133% of the mean inter-stimulus interval (see below).

B) Stimulus-Oriented condition: Stimuli were randomly selected numbers (range 0-299; *Numbers* task) or randomly selected letters of the alphabet (*Letters* task).

Successive stimuli always differed from one another, except for the final stimulus of the block, which was a repeat of the previous stimulus. This stimulus was the last one to make its way from the bottom all the way to the top of the viewing area; additional stimuli were presented subsequently, but the block was terminated before these stimuli reached the top of the screen. In both tasks, subjects were instructed to press a button with their index finger each time a stimulus passed the red marks at the centre of the viewing area, and to press with their middle finger when a repeated stimulus appeared. Thus, this condition involved engagement with the external environment, but little requirement to engage in internal processing of the presented stimuli, since subjects

needed only to process the stimuli in a “shallow” manner (i.e. making same / different judgments), and successive stimuli were always visible on the screen.

C) Stimulus-Independent condition: Stimuli were identical to those presented in condition B. In the *Numbers* task, subjects were instructed to note the first number to be presented in the block and ignore all subsequent stimuli. Subjects mentally counted upwards in sevens from this initial number, pressing a button with their index finger each time they thought of a new number. In the *Letters* task, subjects mentally generated a sequence of letters moving through the alphabet from the first letter they saw, skipping two letters each time (i.e. if the first letter was “A”, subjects would generate the sequence “A .. D .. G .. J .. etc.”). Again, subjects pressed a button with their index finger each time they thought of a new letter. Once they reached the end of the alphabet, subjects were instructed to continue from the beginning. Throughout the block, even when the visually presented information was not task-relevant, subjects were instructed to maintain fixation in the stimulus-presentation area. At the end of each block, subjects used the keypad to input the number or letter they were thinking of at the time the block ended (using an interface that allowed subjects to enter any number between 0 and 999, or any letter of the alphabet). This condition required subjects to withdraw attention from the external environment, since the stimuli served as distracters.

D) Stimulus-Oriented + Stimulus-Independent (SO+SI) condition: In this condition, subjects performed the same task as in condition C. However, the stimuli now conformed to the sequence that subjects were instructed to imagine (e.g., in the *Numbers* task, successive numbers incremented by seven), apart from the final stimulus in each block. In the *Numbers* task, this final stimulus differed from the true continuation of the

sequence by -2, -1, +1, or +2 on 80% of the trials, and by -10 or +10 on the remaining 20%. In the *Letters* task, the final stimulus was either one letter ahead in the alphabet of the true continuation of the sequence, or one letter behind. Subjects were instructed to monitor the externally-presented sequence of items, pressing with their index finger each time a valid continuation of the sequence passed the red marks in the centre of the viewing area. When a target item was presented that did not conform to the sequence, subjects pressed with their middle finger instead. Thus, subjects were required both to generate a sequence of numbers or letters internally (as in condition C) and to monitor the external environment (as in condition B).

Subjects practiced the tasks outside the scanner before the first session. During this practice session, each subject's mean inter-response-interval in the *Stimulus-Independent* condition was recorded (separately for the two tasks), and this was subsequently used as the stimulus-presentation rate in all four conditions. Thus, the mean interval between responses in the condition where subjects were free to respond at their own pace was used as the stimulus presentation rate in the other conditions. This stimulus presentation rate was continually updated throughout the scanning sessions, in accordance with the mean response rate during the *Stimulus-Independent* condition. In this way, the stimulus-presentation and response rates were matched across the four conditions. Stimuli were projected onto a mirror in direct view of the reclining subject, who responded by pressing buttons on a response pad with their right hand. The two tasks were performed in separate scans, each lasting approximately 12.5 minutes, with the order counterbalanced across subjects. Within each session, subjects performed each of the four conditions five times, once with each of the following durations: 10s, 17s, 24s,

31s, and 38s. The order of conditions and durations was randomized, with the constraint that the same condition was never performed twice in a row. Thus, even though the target events in the *Stimulus-Oriented* and *SO+SI* conditions always occurred at the end of the block, subjects were unable to predict exactly when this would be. Each block was preceded by a screen with instructions for that block for 7.5 seconds. At the end of each block, the screen was cleared and instructions for the next block were presented after a delay of 1s. At the end of *Stimulus-Independent* blocks, subjects were given 16s to input the letter or number they were thinking of at the end of the block, before instructions for the next block appeared.

During scans, subjects' eye movements were monitored with an infrared eye tracker (Applied Science Laboratories, Waltham, MA) with remote optics (model 504, sampling rate 60 Hz) custom-adapted for use in the scanner. Due to technical problems, eye-tracking data was only available for 5 of the 14 subjects.

fMRI acquisition

A 3T Siemens Allegra head-only system was used to acquire both T1-weighted structural images and T2*-weighted echoplanar (EPI) images (64 x 64; 3 x 3 mm pixels; echo time (TE), 30 msec) with BOLD contrast. Each volume comprised 48 axial slices (2 mm thick, separated by 1 mm), covering the whole brain. The two functional scans each comprised 239 volumes. Volumes were acquired continuously with an effective repetition time (TR) of 3.12s per volume. The first five volumes in each session were discarded to allow for T1 equilibration effects. Following the functional scans, a 12-minute structural scan was performed.

Data analysis

fMRI data were analyzed using SPM2 software (<http://www.fil.ion.ucl.ac.uk/spm/spm2.html>). Volumes were realigned, corrected for different slice acquisition times, normalized into 2mm cubic voxels using a standard EPI template based on the Montreal Neurological Institute (MNI) reference brain in Talairach space, and smoothed with an isotropic 8-mm, full-width, half-maximum Gaussian kernel. The volumes acquired during the two sessions were treated as separate time series. For each series, the variance in the BOLD signal was decomposed with a set of regressors in a general linear model. Each of the four conditions, in each session, was modeled separately with a boxcar regressor, convolved with a canonical hemodynamic response function (HRF), encompassing the time from the presentation of the second stimulus until the end of the block. In this way, the four conditions were modeled in an identical manner. Additional regressors represented (1) the presentation of instructions (jointly for all conditions), (2) the periods after *Stimulus-Independent* blocks where subjects inputted the letter or number they were thinking of at the end of the block, and (3) the presentation of targets in the *Stimulus-Oriented* and *SO+SI* conditions. These regressors, together with regressors representing residual movement-related artifacts and the mean over scans, comprised the full model for each session. The data and model were high-pass filtered to a cut-off of 1/128 Hz.

Parameter estimates for each regressor were calculated from the least mean squares fit of the model to the data. Effects of interest were assessed in a random effects analysis as follows. Eight contrasts were performed, individually assessing the variance

explained by the regressors representing each of the four conditions in the two tasks. These contrasts were entered into a repeated-measures ANOVA, using non-sphericity correction (Friston et al., 2002). Appropriate contrasts for effects of interest were conducted at the second level, separately for the two tasks. Statistical parametric maps (SPMs) of the minimum t statistic across these two orthogonalized contrasts were generated; these SPMs were converted into SPMs of the Z statistic in a conjunction analysis (Friston, Holmes, Price, Büchel & Worsley, 1999) via associated p values. Thus, it is unlikely that the activations reported below are due to processes specific to one or the other task, since they were observed in both. Contrasts were thresholded at $p < .05$ corrected for multiple comparisons across the whole brain volume (except where stated).

Brain-behavior relationships

In order to assess brain-behavior relationships in the baseline task, fMRI data was analyzed as above, with the following changes. The general linear model for each subject, in each session, consisted of one regressor constructed by convolving a series of delta functions, representing the presentation of each target in the baseline condition, with a canonical hemodynamic response function. A second regressor represented the parametric modulation of this regressor by $\log(\text{RT})^1$, where RTs faster than 100 ms or slower than 1000 ms were replaced with the mean. Along with regressors representing movement-related artifacts and the mean over scans, these two regressors comprised the full model for each session. Effects of interest were assessed by forming contrasts

¹ Reaction time distributions are generally positively skewed (Luce, 1986). In order to maximize the power of this analysis, $\log(\text{RT})$ was therefore chosen as a regressor so that relatively slow RTs did not account for a disproportionately large amount of the variance between trials.

separately for the two regressors representing the modulation of target-related activity by RT (one for each task) and entering these into a repeated-measures ANOVA (with non-sphericity correction). A conjunction analysis was then performed by calculating an SPM of the minimum t statistic across these two contrasts, and converting this into an SPM of the Z statistic via associated p values.

RESULTS

Behavioral data

The mean inter-stimulus interval (i.e. time between successive stimuli passing through the centre of the stimulus-display area) was 1.41s in the *Letters* task and 1.98s in the *Numbers* task ($F(1,13)=9$; $p=.012$). Neither the mean inter-stimulus interval nor the mean inter-response interval differed reliably between conditions (*Stimulus-Oriented*, *Stimulus-Independent*, *SO+SI*, and *Baseline*), and nor were there any Task (*Letters* vs *Numbers*) x Condition interactions (all $F_s(1,13) < 3$; n.s.). Thus, both stimulus-presentation and response rates were successfully matched across the four conditions. Eye-movement data (available for 5 of the 14 subjects) were analyzed by calculating the proportion of time spent fixating within the stimulus-presentation-area in the *Stimulus-Oriented*, *Stimulus-Independent* and *SO+SI* conditions. In the *Letters* task, the proportion of time spent fixating the stimulus-presentation area was 95%, 97%, and 93% in these three conditions, respectively. The corresponding figures for the *Numbers* task were 91%, 84%, and 87%. These figures did not differ reliably between tasks or conditions, and nor was there a

reliable Task x Condition interaction ($F(1,4) < 3$; n.s.). Thus, although data were only available for small sample of the whole group, the results suggest that subjects were able to maintain fixation well during the *Stimulus-Independent* condition (even though they were instructed to ignore the visual display), and that the proportion of time spent fixating the central stimulus-presentation area did not differ reliably between conditions or tasks.

[Table 1 about here]

Full behavioral data for each of the four conditions, in the two tasks, are presented in Table 1. Subjects were able to carry out the tasks adequately in all conditions. In the *Stimulus-Oriented* and *SO+SI* conditions, each subject was presented with five targets in the *Letters* task and five in the *Numbers* task (one in each block). The mean number of non-targets was 79 in the *Letters* task and 60 in the *Numbers* task. The proportion of hits and correct rejections were used to calculate d' scores, which were analyzed in a 2 (Task: *Letters* vs *Numbers*) x 2 (Condition: *Stimulus-Oriented* vs *SO+SI*) repeated-measures ANOVA. Accuracy was lower in the *SO+SI* condition than the *Stimulus-Oriented* condition ($F(1,13)=62$; $p < .001$). There was no main effect of Task ($F(1,13)=3$; n.s.), but there was a significant Task x Condition interaction ($F(1,13)=32$; $p < .001$), since the difference in accuracy between the two conditions was greater in the *Letters* than the *Numbers* task. Accuracy in the *Stimulus-Independent* condition was calculated by counting the number of responses made by each subject in each block. This was used to generate the correct target stimulus that should have been reported at the end of the block,

if subjects had correctly maintained an internal representation of the sequence of numbers or letters throughout the block. Any response within one step of the target (e.g. plus or minus 7 in the *Numbers* task) was counted as correct. There were no reliable differences between the two tasks in the behavioral data for the *Baseline* or *Stimulus-Independent* conditions ($t(13) < 0.9$; n.s.).

Neuroimaging data

[Figure 2 about here]

[Table 2 about here]

First we investigated regions showing relatively high activity during the *Baseline* condition by comparing this condition with the mean of the other three conditions (Table 2; Figure 2). This revealed activity in regions including medial rostral PFC and posterior cingulate / precuneus, in common with previous investigations of rest or baseline conditions (e.g. Binder et al., 1999; Greicius et al., 2003; Mazoyer et al., 2001; McKiernan et al., 2003; Shulman et al., 1997; Raichle et al., 2001). Additionally, there was extensive medial occipital activation, which may have been caused by the additional visual stimulation in the *Baseline* condition (i.e. intermittent illumination of the screen), which did not occur in the other three conditions.

Next we contrasted activity in the *Stimulus-Independent* and *Stimulus-Oriented* conditions (Table 3; Figure 3). The contrast of *Stimulus-Independent* > *Stimulus-Oriented* revealed activity in bilateral SMA / cingulate gyrus, left insula, left premotor cortex, and

left inferior parietal lobule. The reverse contrast (*Stimulus-Oriented* > *Stimulus-Independent*) revealed activity in bilateral medial prefrontal cortex (primarily BA 10, but also BAs 9 and 11), posterior cingulate, lateral occipito-temporal cortex (in the region of the fusiform gyrus), temporal pole, and cerebellum. Thus, activity in medial rostral PFC, which was higher in the *Baseline* condition than the mean of the other conditions, was also associated with a condition requiring attention to the external environment, compared with a condition requiring stimulus-independent thought alone.

[Figure 3 about here]

[Table 3 about here]

Crucially, the analysis of voxels showing a significant relationship between BOLD signal and trial-by-trial fluctuations in *Baseline* RT identified only one significant activation, which overlapped with the medial rostral PFC region identified in the *Stimulus-Oriented* > *Stimulus-Independent* contrast (2, 62, 4; BA 10; $z_{\max}=5.00$; extent: 2 voxels; $p < .05$ corrected). The correlation was negative, i.e. greater activity in this region was associated with trials with *faster* RTs. This rules out an explanation of medial rostral PFC activity during the *Baseline* condition in terms of task-unrelated thoughts (i.e. distraction from the baseline task), since greater activity occurred on trials with better performance (Figure 4)². The overlap between the voxels showing this brain-behaviour

² In a further analysis we specified two parametric regressors, representing a) the response-stimulus interval following each stimulus (i.e. the time from the response to that stimulus until the presentation of the following stimulus) and b) RT (specified linearly, rather than log-transformed, so that both regressors represented linear effects). Even after controlling for the variance accounted for by response-stimulus interval, the regressor representing RT still had a negative correlation with activity in medial rostral PFC (4, 60,

relationship in the *Baseline* condition and the voxels activated by the *Stimulus-Oriented* > *Stimulus-Independent* contrast is remarkable, since the two contrasts were based on separate sets of data (i.e. separate functional scans, collected in different experimental conditions), and different types of analyses (i.e. parametric analysis of brain-behavior correlations in the *Baseline* condition compared with a subtraction between the *Stimulus-Oriented* and *Stimulus-Independent* conditions).

[Figure 4 about here]

Comparisons with the SO+SI condition

The *SO+SI* condition involved aspects of both the *Stimulus-Oriented* and *Stimulus-Independent* conditions. Subjects were required to process incoming sensory information (as in the *Stimulus-Oriented* condition) and also generate information internally (as in the *Stimulus-Independent* condition). Thus, by comparing activity in the *SO+SI* condition with the *Stimulus-Oriented* condition, we were able to isolate activity related to the requirement to generate information internally, controlling for the requirement to process externally-presented information (which was present in both conditions). This contrast revealed activity in right insula and left inferior parietal lobule (Table 4). At a more liberal threshold of $p < .001$ uncorrected, all of the regions activated in the *Stimulus-Independent* > *Stimulus-Oriented* contrast were also activated in this contrast. Moreover, none of these regions differed in activity between the *Stimulus-Independent* and *SO+SI*

4; BA 10; $z_{\max}=3.46$; extent: 15 voxels; $p < .001$ uncorrected). Thus, the association between medial rostral PFC activity and faster RTs could not be caused simply by faster responses being followed by a longer interval until the next stimulus.

conditions, even at an extremely liberal threshold of $p < .05$ uncorrected. Thus, in the present tasks, the regions involved in generating and processing internally-represented sequence information were similar, regardless of whether subjects additionally processed externally-presented information (as in the *SO+SI* condition) or ignored such information (as in the *Stimulus-Independent* condition).

Next, we contrasted the *SO+SI* condition with the *Stimulus-Independent* condition. This allowed us to isolate activity related to the requirement to process externally-presented information, controlling for the requirement to generate information internally. The contrast revealed bilateral activity in lateral occipital areas (similar to those activated in the *Stimulus-Oriented > Stimulus-Independent* contrast), as well as left cerebellum (Table 4). In the right hemisphere this large cluster of occipital activity extended superiorly into superior parietal cortex (BA 7). The reverse contrast (*Stimulus-Independent > SO+SI*) revealed activity in medial frontal (BA 6) and medial occipital cortex (BA 18).

[Table 4 about here]

Notably, the contrast of *SO+SI > Stimulus-Independent* did not lead to activation in medial rostral PFC, despite the activation of this region in the contrast of *Stimulus-Oriented > Stimulus-Independent*. This remained true even at a threshold of $p < .05$ uncorrected. Thus, medial rostral PFC activity was not associated simply with any condition requiring attention to externally-presented information. Rather, activity in this region was associated specifically with the low-demand conditions that involved attention

towards the external environment but did *not* require subjects to generate information internally. This can be seen by contrasting activity in the *Stimulus-Oriented* condition with activity in the *SO+SI* condition (Figure 5; Table 4). Both conditions required subjects to attend to the stimuli presented to them. However, the *Stimulus-Oriented* condition (which required subjects simply to remain vigilant to the sequence of stimuli, and did not require attention to any internally-generated information) was associated with substantial activation in bilateral medial rostral PFC, posterior cingulate, and temporal pole, along with right temporo-occipito-parietal junction, and left cerebellum.

[Figure 5 about here]

Task difficulty

Previous studies have suggested that activity in medial rostral PFC is inversely related to task difficulty (McKiernan et al., 2003). Since medial rostral PFC activation in the present study was greater in the low-demand *Baseline* and *Stimulus-Oriented* conditions than the more demanding *Stimulus-Independent* and *SO+SI* conditions, the question arises of how closely this activation mirrors the relative difficulty of these conditions. We therefore investigated signal change across the various conditions in medial rostral PFC (10mm radius sphere, centered on the peak voxel identified in the analysis of brain-behavior correlations: 2, 62, 4). Additionally, we re-analyzed the data collected by Gilbert et al. (2005) to investigate signal change in the same region. The results of these two analyses established a double dissociation between BOLD signal and task difficulty, as indexed by behavioral performance (i.e. RT and accuracy).

[Figure 6 about here]

In the first analysis, we investigated differences between the *Stimulus-Oriented* and *SO+SI* conditions in the present study. The difference in performance between these two conditions was much greater in the *Letters* than the *Numbers* task (see *Behavioral data*). Thus, if signal change in medial rostral PFC simply reflected task difficulty, the difference in BOLD signal between the *Stimulus-Oriented* and *SO+SI* conditions would be predicted to be larger in the *Letters* than the *Numbers* task. However, this was clearly not the case; if anything the difference in BOLD signal between the two tasks was in the opposite direction (see Figure 6A). In order to statistically verify this dissociation between BOLD signal and behavioral data, we first normalized the two types of data so that they were in comparable units. All behavioral data points (i.e. the 28 data points corresponding to the data from the Letters and Numbers task for each subject) were transformed linearly into z-scores, so that the mean of these 28 data points was zero and the standard deviation was 1. A similar transformation was performed on the BOLD data. Thus, both sets of data had the same mean and standard deviation. These z scores were then entered into a 2 (Task: Letters/Numbers) x 2 (Dependent-Variable: Behavioral/BOLD) repeated-measures ANOVA³. This resulted in a significant Task x Dependent-Variable interaction ($F(1,13)=17$; $p < .005$).

In the second analysis, we re-analyzed the data collected by Gilbert et al. (2005), in which subjects performed three different tasks that could either be accomplished on the

³ In this analysis (and all other analyses with Dependent-Variable as a factor), the factors were arranged so that a significant interaction represents deviation from an inverse relationship between BOLD signal and task difficulty.

basis of externally-presented or internally-generated information. In all three tasks, medial rostral PFC was more active during phases of tasks where subjects attended to externally-presented information than phases where they attended to internally-generated information. In one of the tasks (task 2), there was no reliable difference in either error rates or RTs between the stimulus-oriented and stimulus-independent phases. RTs were 33 ms faster and error rates were 0.9% higher in the stimulus-independent than the stimulus-oriented phases ($F(1,11) < 1.05$; $p > .3$ for both RTs and error rates). However, BOLD signal in medial rostral PFC was significantly higher in this task during the stimulus-oriented than the stimulus-independent phases ($t(11)=4.2$; $p < .005$; see Figure 6B). Thus, it is possible to observe differences in medial rostral PFC activity between conditions requiring attention to externally-presented information and conditions requiring information to be generated internally, even in the absence of behavioral differences between these conditions. After normalizing the data as above, this led to a significant Condition (Stimulus-Independent/Stimulus-Oriented) x Dependent-Variable (Behavioral/BOLD) interaction ($F(1,11)=18$; $p < .005$), using RT as the behavioral measure. Results were similar if error-rate was used as the behavioral measure ($F(1,11)=7.0$; $p < .03$). In the other two tasks investigated by Gilbert et al. (2005), RTs were slower and error rates higher in the stimulus-independent conditions, but these differences in behavioral data between the stimulus-independent and stimulus-oriented conditions did not correlate with BOLD signal in medial rostral PFC (see Gilbert et al., 2005). Finally, we repeated the analyses described above, looking at signal change in just the peak voxel identified in the analysis of brain-behavior correlations (2,62,4). The

results of these analyses were similar to those presented above; all significant results remained significant, and all non-significant results remained non-significant.

In summary, data from the present study show that it is possible to observe significant variation in behavioral performance in the absence of reliable variation in medial rostral PFC BOLD signal. In addition, data from Gilbert et al. (2005) show that it is possible to observe significant variation in BOLD signal in the same medial rostral PFC region, without any reliable variation in behavioral performance. We therefore conclude from this double dissociation that BOLD signal in medial rostral PFC does not simply reflect “task difficulty”, as measured by RT and error rate (see Gilbert et al., 2005, for further evidence for this conclusion).

DISCUSSION

In the present study, we replicated the finding that relatively high medial rostral PFC activity may be associated with low-demand conditions (see Mazoyer et al., 2001; McKiernan et al., 2003; Shulman et al., 1997 for further examples). However, the results provide additional constraints for theorizing about the causes of “de-activation” during high-demand tasks.

Self-generated thought in low-demand conditions?

Some authors (e.g. McKiernan et al., 2003; Wicker et al., 2003) have suggested that medial rostral PFC activity in low-demand conditions reflects the occurrence of self-generated thought processes such as “mind wandering”, which are 1) *task-unrelated* (i.e.

do not help to accomplish the instructed task), and 2) *stimulus-independent* (i.e. decoupled from information currently available in the sensory environment). However, the present data are inconsistent with this account. If medial rostral PFC activity reflects the occurrence of task-unrelated processes, then greater levels of activity (and hence a greater amount of task-unrelated cognition) should be accompanied by worse behavioral performance, because subjects will be distracted from the task. In fact, we observed the reverse pattern of data. Activity in medial rostral PFC was functionally related to performance in the *Baseline* task, since it was associated with *faster* RTs. This activity, therefore, cannot be attributed to the occurrence of task-unrelated processes.

We also found that performance of simple tasks requiring attention to the external environment but not requiring any information to be generated internally was associated with strong activity in medial rostral PFC (along with posterior cingulate, temporal pole, temporo-occipito-parietal junction and cerebellum), compared with conditions requiring subjects to generate information internally. In other words, medial rostral PFC activity was associated with the state of simply remaining alert towards external stimuli, as opposed to generating information internally. This finding is inconsistent with an account of medial rostral PFC activity solely in terms of stimulus-independent processes (see Gilbert et al., 2005 for further evidence). We therefore suggest that, in the present study, medial rostral PFC played a role in maintaining attention towards the external environment during low-demand tasks, rather than being active when subjects were distracted from those tasks by task-unrelated, stimulus-independent thought.

It is somewhat counter-intuitive that the simple *Baseline* condition, which involved minimal stimulus processing, was associated with increased BOLD signal in

many brain regions, compared with conditions involving more extensive stimulus processing or manipulation of internally-represented information. This suggests that the state of simply remaining alert to the external environment, without engaging in complex internal processing of stimuli, is in some way “special”, leading to increased activity in certain brain regions. However, this neurophysiological observation is paralleled by the behavioral literature on reaction time. Although it is well established that RT may decrease as the number of choices decreases (Hick, 1952), responses are particularly fast in situations involving only a single stimulus and a single response (e.g. Leonard, 1959). In such situations the correct response may be chosen without evaluating the stimulus. Frith and Done (1986) have therefore proposed that performance in simple reaction time tasks may utilize a special “fast route” for responding in situations without stimulus or response uncertainty. The current results support this model, and suggest that medial rostral PFC may play a role in facilitating this route for action. These results are in good agreement with recent neuropsychological evidence indicating the medial frontal lesions may be associated with poor performance in simple RT tasks (Stuss et al., 2002; 2005), even in the context of relatively preserved performance in more complex tasks (Burgess, Bird, Gilbert, Husain & Simons, in prep; cf Henderson, Harrison & Kennard, 2001).

Implications for theoretical accounts of rostral PFC function

The proposal that medial rostral PFC may be involved in attention towards the external environment is consistent with the “gateway” hypothesis of rostral PFC function (Burgess, Simons, Dumontheil & Gilbert, 2005; Burgess, Gilbert, Okuda & Simons, in press; Gilbert, Frith & Burgess, 2005; Simons et al., in press-a, in press-b; for related

accounts see Christoff & Gabrieli, 2000; Christoff et al., 2003). According to this hypothesis, rostral PFC activity is not associated exclusively with either internally- or externally-oriented cognitive processes; rather it is associated with situations that require deliberate *biasing* of the attentional balance between current sensory input and internally-generated thought.

Low-demand baseline tasks may involve this attentional biasing precisely because they encourage task-unrelated, stimulus-independent thought, whilst still requiring subjects to maintain watchfulness towards external stimuli. Previous studies have shown that highly monotonous tasks (e.g. Antrobus, 1968), or tasks with a high degree of automaticity (e.g. Teasdale et al., 1995), are associated with an elevated level of task-unrelated, stimulus-independent thought. Thus, performance of tasks with these characteristics (such as the *Baseline* condition in the present study) will benefit particularly from deliberate biasing of attention towards externally-presented information, in order to overcome the tendency towards task-unrelated, stimulus-independent thought. By contrast, tasks with less of a tendency to encourage self-generated thought will not be so dependent on this form of attentional biasing.

A similar argument may be applied to the state of “rest”. Neuroimaging studies that investigate rest may be compared with earlier studies of sensory deprivation, which often employed similar experimental conditions. For instance, in a study by Zuckerman et al. (1962), subjects “were in total darkness and wore earphones connected through an intercom system to a microphone in the adjoining room. When the experimenter was not using this microphone to ... communicate with [them], ... ‘white noise,’ came through it” (p. 2). This perceptual isolation lasted for seven hours. Zuckerman et al. (1962) suggest

that “subjects were more oriented toward ‘external’ stimuli in the earlier part of isolation but became increasingly preoccupied with internal stimuli ... toward the end. It is as if the subjects give up trying to get something from the external world ... and shift their attention to internal events” (p. 13). We propose that the medial rostral PFC activity that is frequently observed during neuroimaging studies of rest (which, of course, have a duration of well under seven hours) may correspond with the psychological process of “trying to get something from the external world”. Thus, even when subjects are not explicitly instructed to attend to events in the external environment (e.g. during rest), they may nevertheless attempt to do so⁴.

This account has some similarity with the “default mode” hypothesis, which attributes activity in medial rostral PFC during rest and baseline conditions (along with other areas, including posterior cingulate) to a process whereby “[i]nformation broadly arising in the external and internal milieu is gathered and evaluated” (Raichle et al., 2001, p. 682). The present results are broadly consistent with this hypothesis. However, although Raichle et al. (2001) suggest that activity in medial rostral PFC is attenuated by “attention-demanding, goal-directed activities”, the present results extend this hypothesis by showing that it is not necessarily the “goal-directedness” of a task that determines activity in this region. In the present study, there is no reason to suppose that the *Baseline* and *Stimulus-Oriented* conditions were less goal-directed than the *SO+SI* and *Stimulus-*

⁴ It is not clear whether a rest condition would have led to greater medial rostral PFC activation in the present study than the *Baseline* condition. However, a study by Christoff et al. (2004), which contrasted a low-demand two-choice RT task with a rest condition, failed to observe any difference between the two conditions in medial PFC (although rest condition was associated with activation in other regions). This suggests that low-demand tasks may lead to comparable levels of activation in medial rostral PFC to the state of “rest”.

Independent conditions. Thus, it does not seem that any goal-directed task will lead to “deactivation” of this area. Rather, we propose that this region plays a specific role in particular types of goal-directed tasks (e.g. deliberate biasing of attention towards externally-presented information), which it may also play during the state of conscious rest. One consequence of this view is that although medial rostral PFC activity may well be associated with easier tasks in some circumstances, this need not always be the case. The present results, along with the results of Gilbert et al. (2005), support this hypothesis by demonstrating a double dissociation between “task difficulty” (as measured by behavioral performance) and BOLD signal in medial rostral PFC.

The hypothesis that rostral PFC plays a role in modulating the attentional balance between stimulus-oriented and stimulus-independent thought (rather than being exclusively involved in one or the other type of process) would also apply to neuroimaging studies investigating mentalizing and other self-referential processes (see Frith & Frith, 2003). In such studies, subjects are presented with stimuli but need to interpret them with reference to unobservable (i.e. internally-represented) mental states. This interplay between stimulus-oriented and stimulus-independent thought may explain the recruitment of rostral PFC. Thus, the present framework provides the outlines of an account that could explain the role of rostral PFC in a wide range of processes, from simple vigilance towards the external environment (as in the present study) to complex evaluative processing (as in studies investigating mentalizing). However, there are many remaining questions to be resolved by future studies, concerning the precise operating dynamics of this system (such as the relationship between lateral and medial subregions

of rostral PFC; for discussion see Burgess et al., 2005, in press; Gilbert et al., 2005; Simons et al., in press-a, in press-b).

The roles of posterior brain regions

The present study also identified a network of other regions involved in the experimental tasks. First, attention to externally-presented letters and numbers was associated with activity in bilateral lateral occipito-temporal regions, extending into superior parietal cortex in the right hemisphere. Second, generating well-learned sequential information (i.e. sequences of numbers, or letters of the alphabet) was associated with activity in a network of insula, inferior parietal, and premotor regions. These findings are consistent with earlier studies implicating similar regions of lateral occipital cortex in the processing of visual alphanumeric stimuli (e.g. Eger, Sterzer, Russ, Giraud & Kleinschmidt, 2003; Flowers et al., 2004) and similar parietal and premotor regions in the processing of sequentially organised information (e.g. Schubotz & von Cramon, 2002). It is interesting that the *Stimulus-Independent* condition (requiring visual stimuli to be ignored) was associated with activity in visual cortex (BA 18), compared with the *SO+SI* condition, which required subjects to attend to visual information. One possible explanation of this finding is that the *Stimulus-Independent* condition required subjects to engage in visual imagery, which has been associated with activity in nearby medial occipital areas (Kosslyn et al., 1999). An alternative explanation might be that subjects paid greater attention to the low-level visual features of the display (e.g. the “snow” pattern used to degrade the stimuli) when they had to ignore the alphanumeric characters that were presented in the *Stimulus-Independent* condition.

Along with medial rostral PFC, another region that was more active in the present study in conditions which did not require stimulus-independent thought was the posterior cingulate. Medial rostral PFC and posterior cingulate are often co-activated in neuroimaging studies, including our earlier study of stimulus-oriented versus stimulus-independent thought (Gilbert, Frith & Burgess, 2005; see also Greicius et al., 2003; Johnson et al., 2002; Raichle et al., 2001; Small et al., 2003, for further examples). However, one potential difference between the roles of these two regions is that the posterior cingulate may play a greater role in tasks involving orienting of attention towards particular regions of space (Hopfinger, Buonocore & Mangun, 2000; Olson, Musil & Goldberg, 1996), whereas medial rostral PFC may be more involved in nonspatial orienting of attention towards the external environment. For instance, Mesulam, Nobre, Kim, Parrish, and Gitelman (2001) found that activity in posterior cingulate, but not medial PFC, correlated with RT reductions in a spatial cueing task. By contrast, the results from the present study (along with previous studies by Mazoyer et al., 2002 and Naito et al., 2000) suggest that faster RTs in a nonspatial vigilance tasks are associated with activity in medial rostral PFC regions, but not posterior cingulate.

Conclusion

The present results corroborate previous findings that medial rostral PFC activity may be associated with low-demand conditions (e.g. Mazoyer et al., 2001; McKiernan et al., 2003; Shulman et al., 1997). However, this activity was functionally related to performance in these conditions and was dissociable from behavioral measures of task difficulty. We therefore conclude that medial rostral PFC plays a role in maintaining

attention towards the external environment during low-demand conditions, rather than simply being responsible for task-unrelated and stimulus-independent thought processes. In other words, although such processes may be more common during low-demand conditions (Antrobus, 1968; Giambra, 1995; Teasdale et al., 1995), their occurrence does not provide a sufficient explanation of activity in medial rostral PFC.

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Table 1. Behavioral results (between-subject standard deviations shown in brackets).

Condition	<i>Numbers</i> task		<i>Letters</i> task	
<i>Baseline</i>				
Mean RT	322	(47)	306	(52)
<i>Stimulus-Independent</i>				
% correct	77	(25.8)	84	(19.5)
<i>Stimulus-Oriented</i>				
False alarms / %	1	(1.46)	0	(0.45)
Hits / %	97	(8.23)	99	(5.35)
d'	3.47	(0.44)	3.77	(0.24)
<i>SO+SI</i>				
False alarms / %	1	(1.46)	3	(2.88)
Hits / %	87	(8.23)	66	(17.1)
d'	3.10	(0.74)	2.30	(0.41)

Note: RTs are only available for the *Baseline* condition, since this was the only condition that required speeded responses.

Table 2. Significant clusters of activation ($p < .05$ corrected) in the contrast of the *Baseline* condition with the mean of the other three conditions

Region	BA	Hemisphere	x	y	z	Z _{max}	N voxels
Medial frontal cortex	10	L	-20	62	14	5.0	5
	8	R	2	56	44	4.9	3
	9/10/24/ 32	B	-4	44	12	6.6	1126
	8	L	-6	34	54	6.1	170
	11	B	2	34	-14	5.0	24
	24	R	6	24	2	5.2	13
Lateral frontal cortex	47	R	42	36	-14	5.9	49
	11/47	R	26	34	-14	5.2	10
	47	L	-42	30	-12	6.7	217
	8	L	-30	28	44	5.0	5
Striatum	-	R	12	20	0	5.0	7
Temporal pole	38	R	32	18	-36	5.2	7
Caudate nucleus	-	L	-4	16	-2	4.9	4
Lateral temporal cortex	21/22	L	-58	-6	-10	6.5	1132
	20/21/22/ 38	R	54	-26	22	7.6	3217
	21/22	R	70	-32	4	5.0	8
	22	L	-40	-34	18	6.1	131
Thalamus	-	B	4	-12	8	5.1	12
Central sulcus	3	L	-38	-16	40	5.0	8
Lateral occipito-temporal cortex	37	L	-42	-42	-18	5.2	13
	39	L	-58	-52	26	7.5	1590
Posterior cingulate / precuneus	23/31	B	-8	-44	38	6.6	1331
Lateral occipital cortex	19	R	52	-74	8	4.9	5
Cerebellum	-	R	28	-82	-34	5.3	13
Medial occipito-temporal cortex	17/18/27	B	-10	-90	8	>8	13376

Note: co-ordinates refer to the Montreal Neurological Institute reference brain. Brodmann areas (BA) are approximate. L=left, R=right, B=bilateral.

Table 3. Significant clusters of activation in contrasts between the *Stimulus-Independent* and *Stimulus-Oriented* conditions ($p < .05$ corrected).

Region	BA	Hemisphere	x	y	Z	Z _{max}	N voxels
<i>Stimulus-Independent > Stimulus-Oriented</i>							
Insula	13	L	-34	18	12	5.2	15
SMA / cingulate gyrus	6/32	B	-8	14	46	6.3	173
Premotor cortex	6	L	-24	6	44	5.6	38
Inferior parietal lobule	40	L	-52	-32	48	4.9	5
	40	L	-44	-42	50	5.2	40
Precuneus	-	L	-30	-62	46	5.0	4
<i>Stimulus-Oriented > Stimulus-Independent</i>							
Medial frontal cortex	10	L	-10	68	16	4.8	1
	10	L	-6	64	22	5.1	7
	10	B	0	62	4	5.3	41
	9	L	-6	60	36	5.3	51
	10/11	B	0	48	-16	4.9	8
	11	L	-6	32	-12	5.4	60
	32	R	6	32	-12	4.9	2
	11	B	0	30	-26	5.0	2
Temporal pole	38	R	42	18	-38	5.0	9
	38	L	-28	12	-36	4.9	1
Cerebellum	-	R	38	-44	-24	5.5	32
	-	L	-38	-52	-20	5.1	4
	-	L	-38	-62	-16	4.9	1
Posterior cingulate	23	B	-2	-50	22	5.0	12
Occipital cortex	18/19/37	R	46	-74	-10	7.5	1238
	18/19	L	-42	-78	-4	6.8	659
	18/19	L	-30	-88	18	5.4	86

Note: SMA=supplementary motor area.

Table 4. Significant clusters of activation in contrasts between the *SO+SI*, *Stimulus-Oriented* and *Stimulus-Independent* conditions ($p < .05$ corrected).

Region	BA	Hemisphere	x	y	z	Z _{max}	N voxels
<i>SO+SI > Stimulus-Oriented</i>							
Insula	13	R	32	22	-2	5.0	7
Inferior parietal lobule	40	L	-46	-38	50	6.4	180
<i>SO+SI > Stimulus-Independent</i>							
Lateral occipital cortex	18/19/37	L	-42	-76	-2	7.8	949
	18/19	L	-24	-76	28	6.1	83
Occipital / parietal cortex	18/19/37/7	R	46	-76	-4	7.5	1598
Cerebellum	-	L	-2	-78	-34	5.3	22
<i>Stimulus-Oriented > SO+SI</i>							
Medial frontal cortex	9/10/32	B	-2	46	10	7.2	1450
	8	R	14	50	46	5.3	18
	8	L	-14	40	50	5.5	81
	8	R	14	36	54	5.1	4
Temporal pole	38/28	R	50	12	-30	5.6	113
Cerebellum	-	L	-30	8	-44	5.1	8
Posterior cingulate	31/23	B	-4	-44	34	6.8	682
Temporo-occipito-parietal junction	39	R	56	-64	28	5.6	49
<i>Stimulus-Independent > SO+SI</i>							
Medial frontal cortex	6	R	6	18	54	4.9	3
Medial occipital cortex	18	B	-2	-86	24	5.9	81

FIGURE CAPTIONS

Fig. 1. Schematic illustration of the stimulus display and the various experimental conditions in the *Numbers* task. The stimuli scrolled smoothly and continuously and the stimulus-display area was large enough that up to three stimuli could be seen at any one time. Throughout all conditions, stimuli were degraded with a constantly changing “snow” pattern, to increase the requirement to pay close attention to the external environment when the stimuli were task-relevant.

Fig. 2. Regions showing greater activation in the *Baseline* condition than the mean of the other three conditions ($p < 0.05$ corrected), plotted on slices of the mean normalized structural image ($x=0$; $y=60$; $z=34$). Images follow neurological convention (left/right not flipped).

Fig. 3. Areas of activation in contrasts between the *Stimulus-Independent* and *Stimulus-Oriented* conditions ($p < 0.05$ corrected), plotted on a sagittal slice ($x=4$) of the mean normalized structural image of the 14 participants, and two axial slices (A and B). Images follow neurological convention (left/right not flipped).

Fig. 4. Left: voxels showing a significant correlation between BOLD activity and faster RTs in the *Baseline* task (plotted in red; $p < 0.05$ corrected), and voxels showing significantly greater activity in the *Stimulus-Oriented* than *Stimulus-Independent* condition (plotted in yellow; $p < 0.05$ corrected), plotted on a sagittal slice of the mean

normalized structural image ($x=4$). Right: In a separate analysis, the four quartiles of the *Baseline* RT distribution were modeled separately for each subject. The resulting parameter estimates show that greater activation was associated with trials with faster RTs.

Fig. 5. Regions of activity in the contrast of *Stimulus-Oriented* > *SO+SI*, plotted on the mean normalized structural image ($p < 0.05$ corrected; $x=4$, $y=60$, $z=6$) and percent signal change (compared with mean) associated with the *Baseline* (Base), *Stimulus-Oriented* (SO), *Stimulus-Independent* (SI), and *SO+SI* conditions in medial BA 10 (2, 62, 4). Images follow neurological convention (left/right not flipped). Error bars indicate standard errors.

Fig. 6. Double dissociation between BOLD signal in medial rostral PFC and task difficulty. *A*: difference in d' (left) and BOLD signal (right) between *Stimulus-Oriented* and *SO+SI* conditions, plotted separately for the *Letters* and *Numbers* tasks. The two tasks differ reliably in behavioral data, but not in associated BOLD signal. *B*: RT (left) and BOLD signal (right), plotted separately for *Stimulus-Independent* and *Stimulus-Oriented* phases in Task 2 of Gilbert, Frith & Burgess (2005). The two phases differ reliably in BOLD signal but not in behavioral data. In this study the two phases simply alternated and were modeled with a single regressor yielding just one parameter estimate to represent the difference between conditions. Thus the BOLD signal for the *Stimulus-Independent* condition constitutes a statistical baseline, with a value of zero.

Figure 1

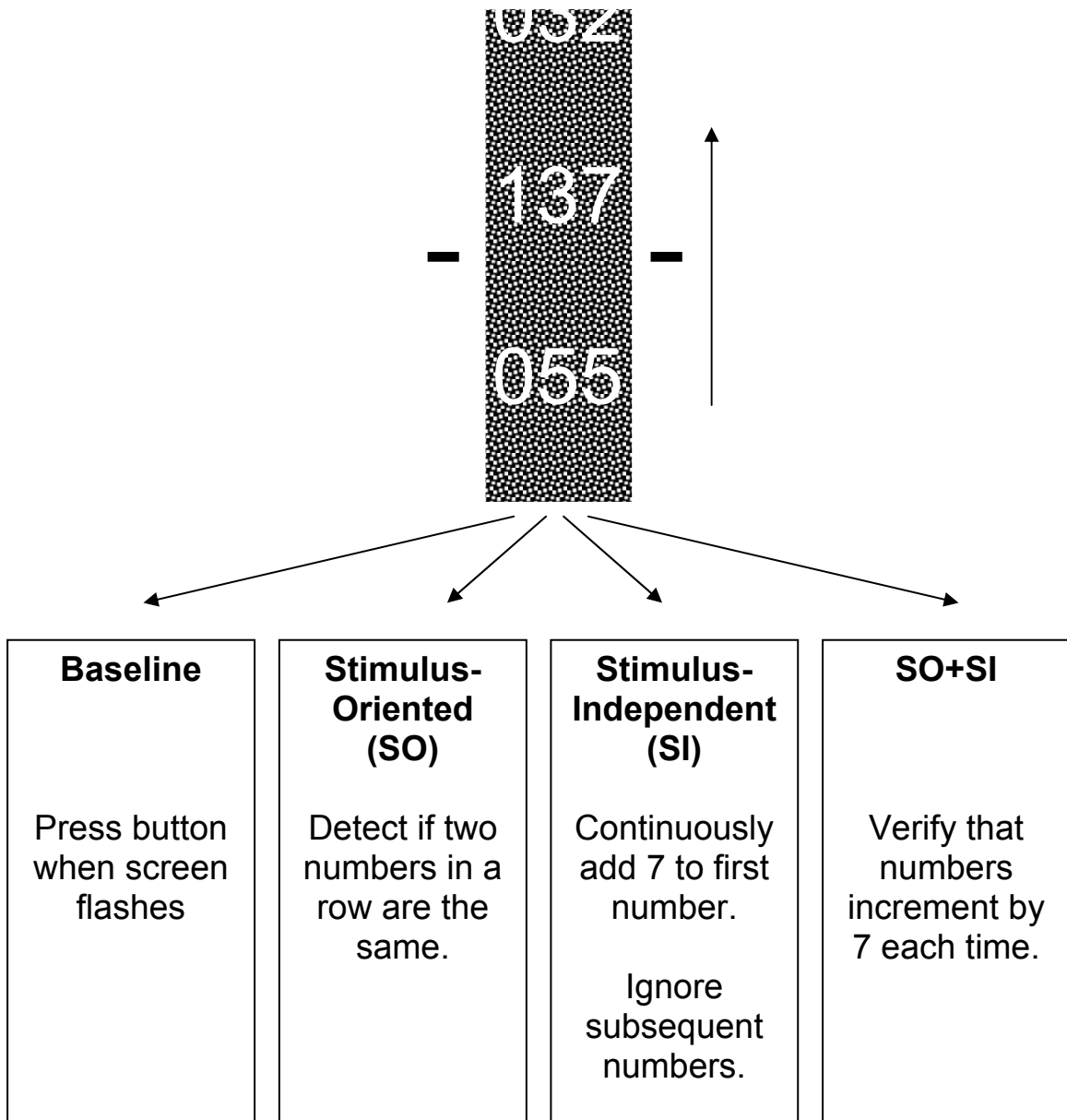


Figure 2

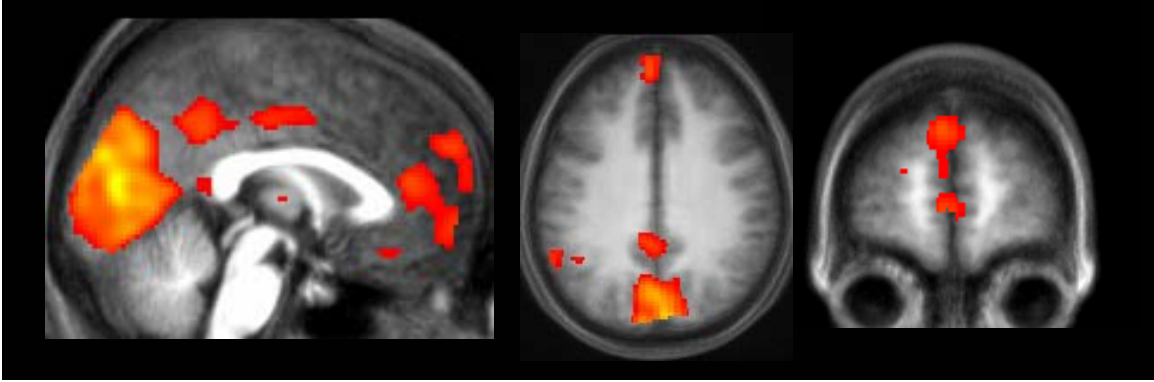


Figure 3

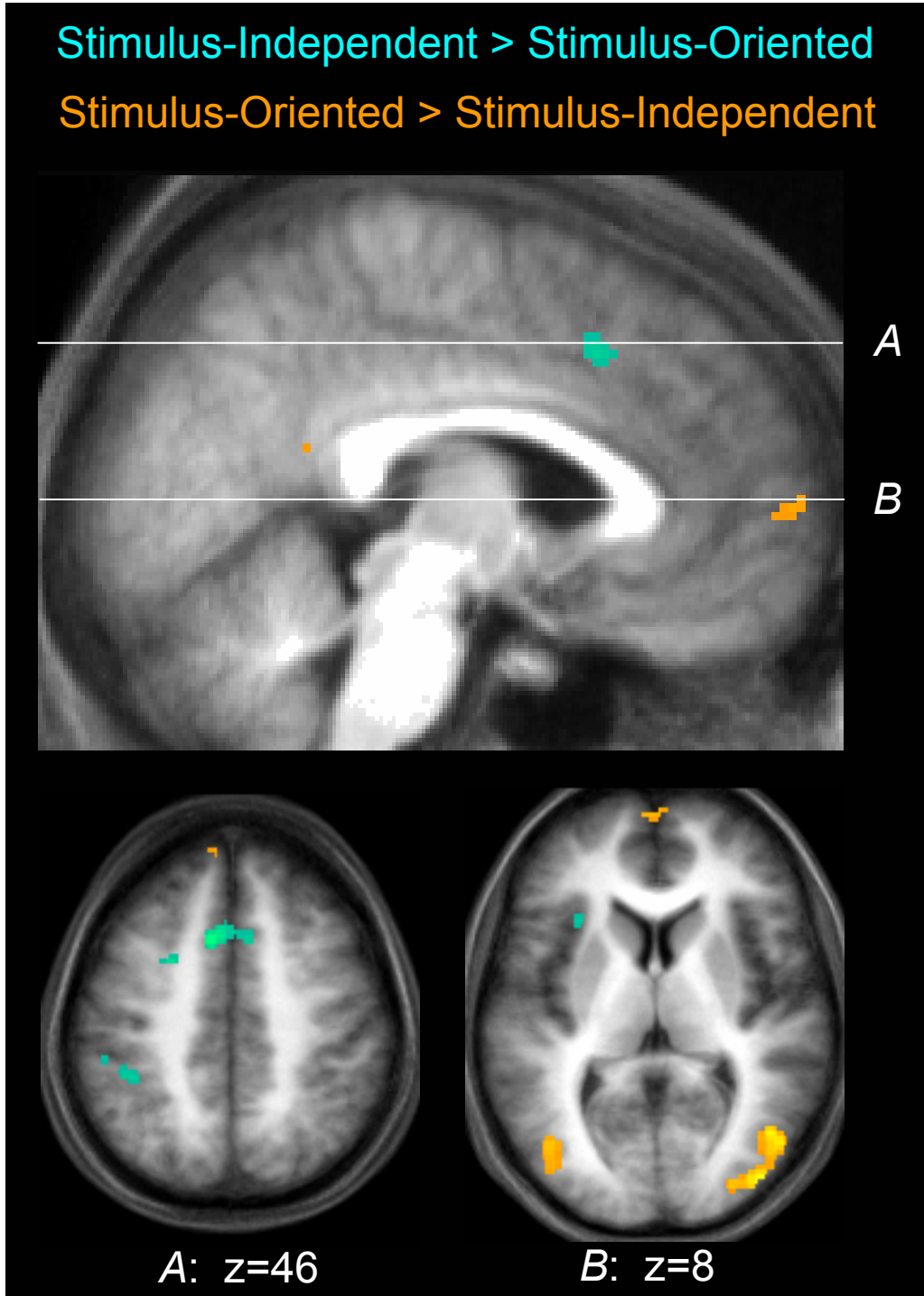


Figure 4

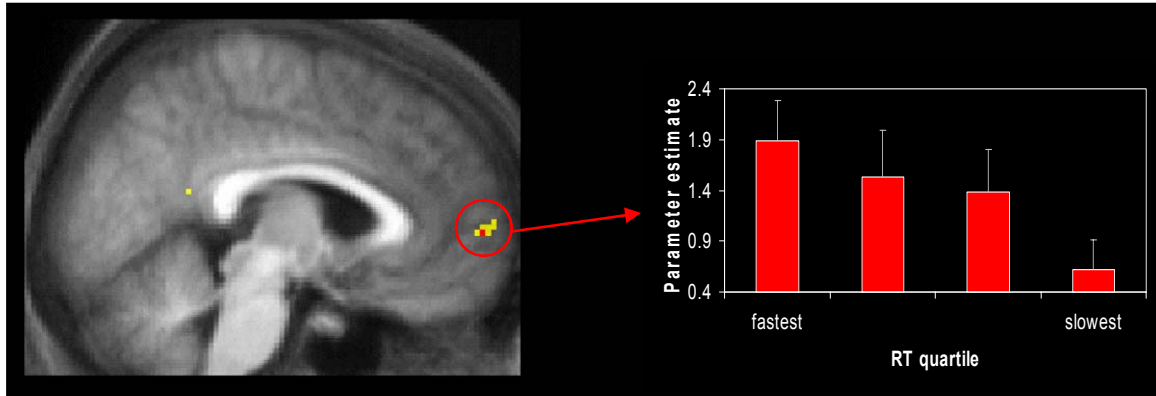


Figure 5

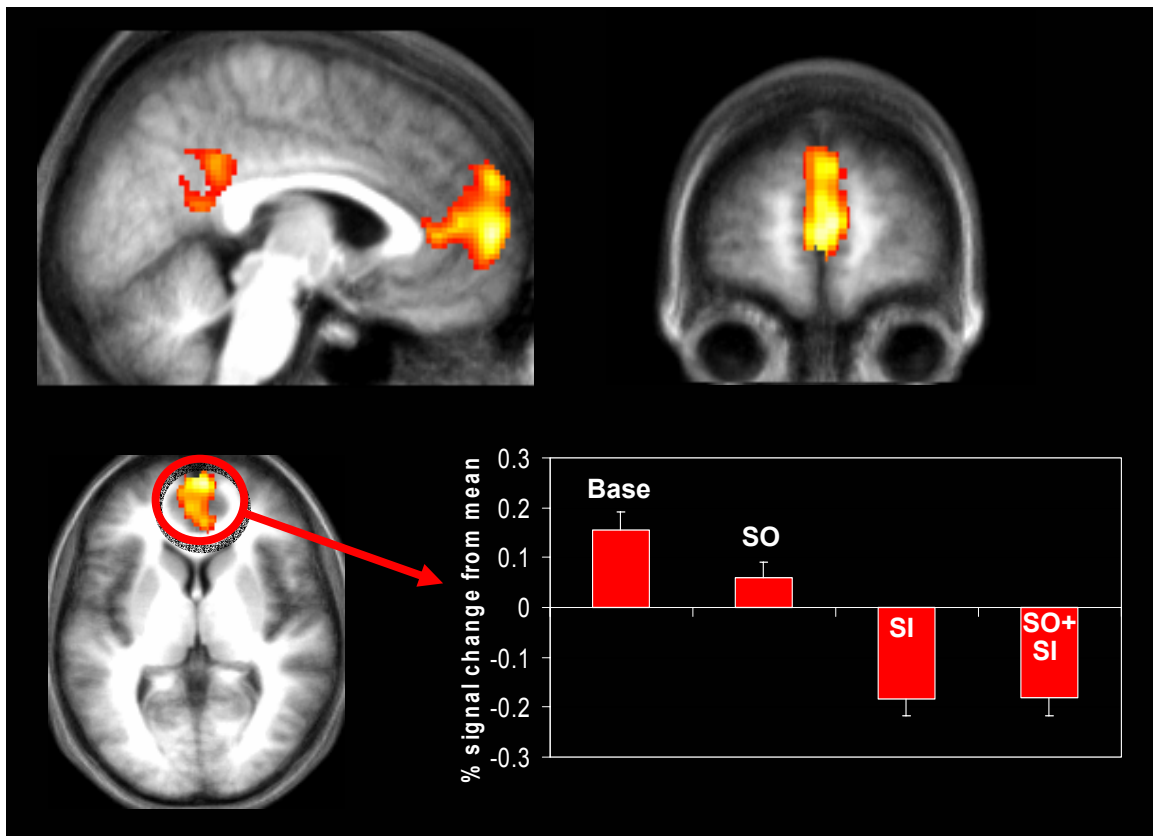


Figure 6

