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Chapter 9

The gateway hypothesis of rostral prefrontal cortex (area 10) function

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Abstract

One of the most fascinating puzzles in cognitive neuroscience concerns the functions of a large brain area known as the rostral prefrontal cortex (or Area 10). This is a sizeable brain region, which is especially large in humans compared with other animals, yet very little is known about what role it plays in cognition. This chapter contains three sections. The first reviews the existing empirical and theoretical evidence. The second presents a new theoretical account of its function that synthesises this evidence. The third describes a recent series of experiments in our laboratory, which demonstrate the plausibility of the theory. Rostral prefrontal cortex (rostral PFC) is identified as subserving a system that biases the relative influence of stimulus-oriented and stimulus-independent thought. This cognitive control function (and its product) is used in a wide range of situations critical to competent human behavior in everyday life, ranging from straightforward "watchfulness" to complex activities such as remembering to carry out intended actions after a delay, multitasking, and aspects of recollection. In everyday terms, these are situations that require one to be particularly alert to the environment, to deliberately concentrate on one's thoughts, or involve conscious switching between these states.

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Introduction

> Attempts to define . . . executive function encounter . . . a . . . difficulty: no single exemplary task or even subset of tasks provides an adequate ostensive definition. It is often necessary to fall back on consensus definitions drawn from the common sense of the "man in the street" or poll the collective wisdom of "distinguished experts in the field" . . . these tend to be wide-ranging catalogues of examples of intelligent behavior and to avoid entirely discussions of underlying process (Rabbitt, 1997, p. 30).

The part of the frontal lobes that is foremost in the brain has many names. The most common of these are: "anterior prefrontal cortex" (anterior PFC), "the frontal pole," "frontopolar cortex," and "rostral prefrontal cortex." Of these, we favor the use of the term "rostral" since the term is equivalent to others that are used to denote regions of the brain (e.g. caudal, dorsal, lateral, medial, ventral). However these terms all refer to a region, which broadly corresponds to the cytoarchitectonic area known as Brodmann Area 10 (BA 10). This is probably the region of the brain whose function is least understood, although there is good reason for suspecting that it plays a critical role in human cognition. For instance, this is a very large brain region in humans: in volumetric terms probably the largest single architectonic region of the frontal lobes (Christoff et al. 2001). Indeed, Area 10 of the human right hemisphere alone (approx. 14,000 mm^3) makes up 1.2% of the *entire* brain volume (Semendeferi et al. 2001). Given that the brain may consume as much as 20% of the oxygen we extract from the air that we breathe (Raichle et al. 2001), there must surely be some evolutionary advantage to having such a large brain region (or rather, the capacities that it enables). Moreover, rostral PFC is in relative terms twice as large in the human brain as in any of the great apes (Semendeferi, Armstrong, Schleicher, Zilles, & Van Hoesen, 2001). And finally, this region is possibly the last to achieve myelination, and it has been argued that tardily myelinating areas engage in complex functions highly related to the organism's experience (Fuster, 1997, p. 37). These are all good reasons to imagine that the rostral PFC may support cognitive processing which is especially important to humans.

However, very little is known about the functions of rostral PFC. There are many reasons for this situation: animal studies of this region are problematic; the very fact of the structural difference between humans and other animals creates doubt as to the transferability of findings from one species to another, and animal lesion studies of this region are hindered by practical anatomical considerations. Other cognitive neuroscience methods also face limitations.

For instance, electrophysiological methods do not presently have the required spatial resolution to separate subregions of the frontal lobes, and transcranial magnetic stimulation studies of rostral PFC may be difficult for anatomical reasons. Thus virtually the only significant evidence one might call upon from methods other than functional imaging comes from human lesion studies. These however are difficult and costly: Area 10 lesions are not common, and typically do not produce "hard" neurological signs (such as hemiparesis, marked aphasia, etc.). So unless they are the result of trauma, rostral lesions are often not detected unless (or until) they are large, covering many other brain regions in addition to Area 10. This then raises the question of which of the symptoms can be attributable specifically to the rostral aspect of the lesion, usually necessitating a group study using the overlapping lesion method (see below). However since there is no straightforward pathology to lesion site correspondence, the pattern will typically be made more difficult by issues of the effects of different pathologies. These issues are not insurmountable (see for example, Burgess, Veitch, Costello, & Shallice, 2000; Burgess, Veitch, & Costello, submitted), but will necessitate careful and lengthy data collection and analysis, often taking several years. In this context, it is unsurprising that most data relevant to rostral PFC function comes from functional neuroimaging. However, there is a problem with the use of functional imaging as the sole source of data. Rostral PFC activation is found in such a wide variety of tasks that this provides relatively few constraints on theorizing. Local haemodynamic (e.g. blood-flow, blood oxygenation) changes occur in Area 10 during the performance of a very wide variety of cognitive tasks (Grady, 1999), from the simplest (e.g. conditioning paradigms; Blaxton et al. 1996) to highly complex tests involving memory and judgment (e.g. Burgess, Quayle, & Frith, 2001; Burgess, Scott, & Frith, 2003; Frith & Frith, 2003; Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999) or problem-solving (e.g. Christoff et al. 2001). Indeed, one can find activation of the rostral PFC in just about any kind of task, for example, verbal episodic retrieval (Rugg, Fletcher, Frith, Frackowiak, & Dolan, 1996; Tulving, Markowitsch, Criak, Habib, & Houle, 1996); nonverbal episodic retrieval (Haxby et al. 1996; Roland & Gulyas, 1995); semantic memory (Jennings, McIntosh, Kapur, Tulving, & Houle, 1997; Martin, Haxby, Lalonde, Wigges, & Ungerleider 1995); language (Bottini et al. 1994; Klein, Milner, Zatorre, Meyer, & Evans, 1995); motor learning (Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994); rule learning (Strange, Henson, Friston, & Dolan, 2001); shock/ tone conditioning (Hugdahl et al. 1995); nonverbal working memory (Gold, Berman, Randolph, Goldberg, & Weinberger, 1996; Haxby, Ungerleider, Horwitz, Rapoport, & Grady, 1995); verbal working memory (Petrides, Alivisatos, Meyer, & Evans, 1993); spatial memory (Burgess, Maguire, Spiers, & O'Keefe, 2001); auditory perception (Zatorre, Halpern, Perry, Meyer, & Evans, 1996); object processing (Kosslyn et al. 1994; Kosslyn, Alpert, & Thompson, 1995); Tower of London Test (Baker et al. 1996); Wisconsin Card Sorting Test (Berman et al. 1995); reasoning tasks (Goel, Gold, Kapur, & Houle, 1997); intelligence tests such as Raven's Progressive Matrices (Christoff et al. 2001; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997).

Perhaps a meta-analysis of the tasks which most reliably produce rostral PFC activation would isolate the critical processing component supported by this region? Grady (1999) provides an excellent analysis of this sort. She reviewed 90 PET studies showing prefrontal rCBF changes, and concluded that the most heavily represented function of BA 10 is episodic memory, on the grounds that most of the experiments reporting BA 10 activation were using episodic memory paradigms. This was a very useful and carefully conducted review. However it did not take into account the predominance of episodic memory investigations in functional imaging studies. If one takes this into account, a quite different picture emerges. Thus 37/90 (41%) of the studies that Grady considered in her review investigated episodic memory, and 47/90 (52%) of the studies she considered implicated BA 10. However, only 68% of the episodic memory studies were found to cause BA 10 activations, and just 25 (53%) of the paradigms that caused BA 10 activations were episodic memory ones. Furthermore, 7/90 of the studies that Grady considered were investigations of "Working Memory" and 6 of these (86%) showed BA 10 activation. And finally, 6/90 studies investigated conditioning or motor learning, and all 6 (100%) reported BA 10 activation. Thus it is doubtful that, whatever role BA 10 functions play in cognition, they are any more active when people are involved in episodic memory tasks than when they are engaged in other sorts of tasks. As MacLeod, Buckner, Miezin, Petersen, & Raichle (1998) put it, "although . . . BA 10 is routinely activated by episodic memory tasks, it is not uniquely activated by episodic memory tasks" (p. 41; see also Duncan & Owen, 2000).

Theories of rostral PFC (area 10) function

Perhaps because of the widespread nature of the evidence from functional imaging, there are a number of extant theories, each of which seeks to explain some part of the findings. There are, broadly, four categories of these theories:

1. *Episodic memory accounts*: Notwithstanding the criticisms above, the idea that Rostral PFC (area 10) plays some particularly significant role in episodic memory is widespread. This is largely based on evidence from

functional imaging (e.g. Rugg et al. 1996; Tulving et al. 1996). For instance Buckner (1996, p. 156) suggests that "the common activation during episodic retrieval is highly localised, falling at or near Brodmann area 10."

2. *Metacognition*: The theories in this category hold that BA 10 supports processing that perhaps can best be described as "metacognition," that is reflecting on one's own thoughts, or thinking in a very controlled, conscious, or goal-directed mode (e.g. Johnson et al. 2002). For instance, Christoff & Gabrieli (2000, p. 183) describe the role of this region as of "evaluation, monitoring, or manipulation of internally generated information"; and others talk about states of awareness, for example, "felt-rightness" (Moscovitch & Winocur, 2002). Proponents of the "Theory of Mind" perspective, meanwhile, suggest that medial rostral PFC may be "engaged when we attend to our own mental states as well as the mental states of others" (Frith & Frith, 2003, p. 467).

3. *Sum processes*: There are two subcategories of these theories: processing and anatomical. The processing views maintain that rostral PFC supports processing involved in the coordination of potentially independent processing resources (e.g. Ramnani & Owen, 2004). For instance Koechlin and colleagues (e.g. Dreher, Koechlin, Ali, & Grafman, 2002; Koechlin et al. 1999; Koechlin, Ody, & Kouneiher, 2003) maintain that lateral rostral PFC "selectively mediates the human ability to hold in mind goals while exploring and processing secondary goals" (Koechlin et al. 1999, p. 148), with the frontal lobes organized along a posterior to anterior axis as the task being performed becomes more endogenously guided (Dreher et al. 2002). The highest level of this control is exerted by (lateral) rostral PFC when the task rules must be derived from a previous episode (Koechlin et al. 2003). Significantly, Etienne Koechlin was also one of the first people to demonstrate a possible medial–lateral dissociation in rostral PFC function, with a study that implicated medial rostral regions in situations where a subject encounters predictable sequences of stimuli, and lateral polar regions where the subject is performing tasks in sequences contingent upon unpredictable events (Koechlin, Corrado, Pietrini, & Grafman, 2000). (We will return to the issue of lateral–medial functional distinctions later.) Fletcher & Henson (2001) outline an anatomically-based variant, suggesting that rostral PFC operates with other (frontal) brain regions to effect cognitive control, "selecting between processes or goals (rather than between information maintained in WM and stored in LTM). It can also be viewed as another type of monitoring, in which it is the interaction between ventrolateral frontal cortex (VLFC) and dorsolateral frontal cortex (DLFC) processes that is being monitored rather than the information being maintained/manipulated *per se*" (p. 876).

4. *The default mode hypothesis*: This influential account relates specifically to medial rostral PFC, and is motivated by the repeated finding of decreases in activation of medial area 10 relative, usually, to rest, that are found when people perform a wide range of demanding cognitive tasks (Christoff, Ream, & Gabrieli, 2004; Gusnard & Raichle, 2001). Raichle et al. (2001) argue that "when an individual is awake and alert and yet not actively engaged in an attention-demanding task, a default state of brain activity exists that involves . . . the [medial prefrontal cortices] . . . Information broadly arising in the external and internal milieu is gathered and evaluated. When focused attention is required, particularly if this activity is novel, activity within these areas may be attenuated. This attenuation in activity reflects a necessary reduction in resources devoted to general information gathering and evaluation" (p. 682; see also Gusnard, Akbudak, Shulman, & Raichle, 2001; Raichle, 1998).

These hypotheses are all extremely useful, and represent a staggeringly fast advance in our state of knowledge compared with five years or so ago, when virtually no accounts existed. However whilst they all account for some aspects of the empirical data, each of them is incomplete in some respect. This incompleteness takes two forms. First, they typically attempt to either explain medial or lateral rostral PFC functions, but not both, despite suggestions that these regions may work as a functional unit (e.g. Burgess et al. 2003; Koechlin et al. 2000). Second they are incomplete in that they (a) fail to explain all the functional imaging data, and (b) encounter severe problems when it comes to explaining the data from human lesion studies. We will examine the latter challenge below. But let us first consider the incompleteness of these theories from the point of view of the functional imaging data.

We have already shown the episodic memory accounts to be only partial accounts of the totality of the data: BA 10 seems to be involved in the performance of tasks that have no particular episodic memory component. The metacognition accounts are also problematic on two grounds. First there is the confusion concerning the location of the critical area. Thus, for instance Christoff & Gabrieli (2000) refer only to *lateral* regions, yet Zysset, Huber, Ferstl, & Von Cramon (2002), for instance, refer to *medial* rostral PFC as critical for "metacontrol" processes (p. 989). Second, these accounts do not explain why activations in these regions can be seen during tasks which have little obvious "metacognitive" component (e.g. motor learning, eyeblink conditioning). One might perhaps also consider Rabbitt's (1997) criticism here: there is no clear specification of which we are aware of what constitutes a task requiring "metacognitive" processing. Thus there does seem to be some confusion. For instance, would all theorists agree that "Theory of Mind" should be considered a metacognitive process (see Frith, 2002; Zysset et al. 2002)?

The "Sum Process" accounts are also incomplete accounts of the evidence. Lateral BA 10 activations can be seen during quite straightforward tasks, which do not obviously make great demands upon two processes at once. For instance Belin et al. (2002) report BA 10 activations provoked by a simple paradigm involving the detection of sounds of infrequent duration. Additionally, strong BA 10 activations are not always accompanied by strong activations in other parts of the frontal lobes (e.g. Burgess et al. 2003) as the Fletcher & Henson (2001) hypothesis might suggest. Finally, the Default Mode Hypothesis is problematic in that medial rostral PFC activity can differ between conditions that have similar requirements for goal-directed attention (e.g. Zysset et al. 2002). Further data relevant to this point will be presented below.

The hypothesis that we later outline maintains that all of these accounts are however essentially correct in what they cover, and attempts to unify them with one simple hypothesis. But first, we need to consider the constraints the data provide, which can form the basis for theorizing about the functions of Area 10 in humans.

Rostral PFC function: from data to theory

Burgess, Gilbert, Okuda, & Simons (in press) surveyed the available literature and came to the following conclusions:

1. There is very little data concerning the putative functions of rostral PFC other than from functional imaging and a small number of human lesion studies.
2. Functional imaging data provides few constraints on theorizing because rostral PFC activation is found in such a wide variety of tasks.
3. Human lesion data rules out many aspects of the theories from functional imaging.
4. The most promising approach for functional imaging is therefore to start with the possible explanations emerging from lesion data.
5. Functional imaging studies that start from this base suggest that the role of rostral PFC is in the attentional control between stimulus-independent and stimulus-oriented thought.

For full support for these contentions, readers are referred to Burgess et al. (in press). We will, however, cover in brief here aspects of points 3 and 4 before summarizing the constraints from empirical data that we have applied to our theorizing, and outlining in much more detail than in Burgess et al. (in press) an integrative theory of the role of rostral PFC processes in human cognition.

Human lesion data provides valuable constraints for theorizing

As already noted, functional imaging experiments implicate BA 10 in the performance of a very wide range of tasks. One obvious expectation therefore might be that damage to this area in humans would cause impairment on a wide range of cognitive tasks. However the available evidence shows emphatically that this is *not* the case. Consider for instance case AP from Shallice & Burgess (1991a), who was called "NM" when he was investigated by Metzler & Parkin (2000). AP was involved in a serious road-traffic accident when he was in his early twenties, and sustained an open head injury, leading to virtually complete removal of the rostral PFC. However on standard neuropsychological measures of intellectual functioning, memory, perception and even traditional tests of executive function, AP performs within the superior range (see Wood & Rutterford, 2004 for further evidence).

This is not however to say that AP was unimpaired in other regards (Metzler & Parkin, 2000; Shallice & Burgess, 1991a; Wood & Rutterford, 2004). The most noticeable impairment in everyday life was a marked multitasking problem. This manifested itself as tardiness and disorganization, the severity of which ensured that despite his excellent intellect and social skills, he never managed to make a return to work at the level he had enjoyed premorbidly. Shallice & Burgess (1991a) invented two new tests of multitasking to assess these problems. One was a real-life multitasking test based around a shopping exercise, the "Multiple Errands Test," and the second a multitasking test for use in the laboratory or clinic, the "Six Element Test." Despite excellent general cognitive skills, AP and the other cases reported by Shallice and Burgess all performed these tasks below the 5% level compared with age- and IQ-matched controls.

There are now a number of cases reported in the literature who show similar everyday behavioral impairments (see Burgess, 2000 for review) and there is a remarkably consistent finding of involvement of Area 10 amongst them. For instance, in the six cases reviewed by Burgess, all of them had rostral PFC involvement of either the left or right hemispheres (or both). Moreover, all cases to whom the Shallice/Burgess multitasking tests have been administered have failed at least one of them. In addition to these cases, we might now also add the recent case GT described by Bird, Castelli, Malik, Frith, & Husain (2004) who failed the Six Element Test.

Not only is there congruence in the tasks that patients with rostral damage fail, but there is congruence in the tasks that they pass. Most importantly, the data from single cases whose lesions invade rostral PFC (Bird et al. 2004; Eslinger & Damasio, 1985; Goldstein, Bernard, Fenwick, Burgess, & McNeil, 1993; Goel & Grafman, 2000; Shallice & Burgess, 1991a) categorically show that rostral PFC lesions need *not* cause impairments on a wide range of tests of executive function, such as the Wisconsin Card Sorting Test (Grant & Berg, 1948), the Tower of London planning test (and its variants; Shallice, 1982), the Cognitive Estimates Test (Shallice & Evans, 1978) or Stroop paradigms (see Figure 9.1).

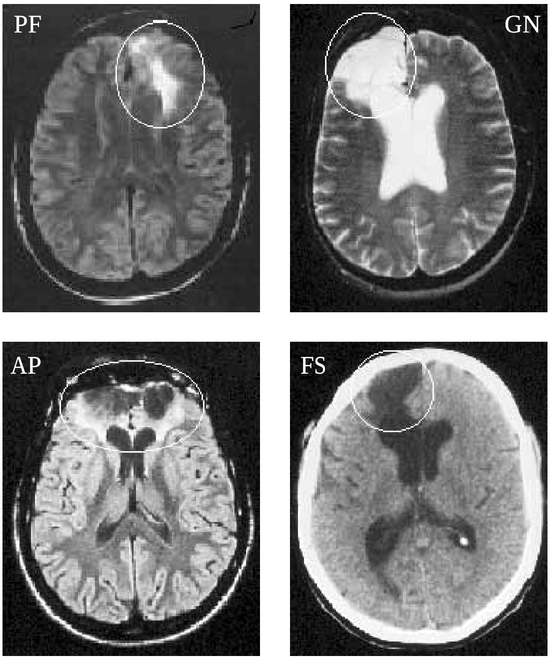

Fig. 9.1 MRI/CT brain scans of four neurological patients with rostral prefrontal damage. All patients achieved superior scores on IQ tests, and all achieved excellent scores on traditional executive tasks such as the Wisconsin Card Sorting and Verbal Fluency tests. However they all showed significant behavioral organization problems in everyday life. (PF: Goel Grafman, 2000; GN: Goldstein et al. 1993; AP and FS: Shallice & Burgess, 1991. Site of rostral lesions are circled. The lesions are different colors because of their differing pathologies and the different methods used to image them. Some scans have been left-right transposed from the originals for ease of understanding, for example, left hemisphere is on the left of figure etc.)

Of course anatomical-behavioral associations made on the grounds of data from single case studies should be treated with caution, since individual cases might be anatomically atypical. However two recent group human lesion studies also convincingly demonstrate that patients with rostral PFC damage do *not* necessarily have widespread cognitive deficits. Thus Burgess et al. (2000) examined a series of 60 acute neurological patients (approximately three-quarters of whom were suffering from brain tumors) and 60 age- and IQ-matched healthy controls on a multitasking test called the Greenwich Test. In this test, subjects are presented with three different simple tasks and told that they have to attempt at least some of each of the tasks in 10 min, while following a set of rules. Despite being able to learn the task rules, form a plan, remember their actions, and say what they should have done, patients with left hemisphere rostral lesions showed a significant multitasking impairment: they were able to perform the individual subtasks perfectly well, but tended not to switch tasks, and when they did, showed a problem following the rules of the other tasks.

A further recent human group lesion study underlines these results (Burgess et al. submitted). In this study, a new version of the Burgess et al. (1996) Six Element Test (SET) of multitasking was given to sixty-nine acute neurological patients with circumscribed focal lesions and sixty healthy controls, using the administration framework of Burgess et al. (2000). The SET differs from the Greenwich Test in that there are more subtasks that have to be attempted (six rather than three), and fewer rules to follow. Compared with other patients, those whose lesions involved the rostral prefrontal regions of the right hemisphere made significantly fewer voluntary task switches, attempted fewer subtasks, and spent far longer on individual subtasks. They did not however make more rule-breaks.

Using human lesion data as a starting point for functional imaging studies

In this laboratory we have taken the constraints presented by human lesion data as a starting point for our functional imaging studies. The multitasking failures in our patients could be characterized as reflecting difficulty with carrying out delayed intentions (i.e. “prospective memory”; Brandimonte, Einstein, & McDaniel, 1996; see also Duncan, Emslie, Williams, Johnson, & Freer, 1996). Prospective memory (PM) tasks differ from working memory tasks principally in that they involve performance of an ongoing task during the delay period, which prevents continuous rehearsal (see Burgess et al. 2001 for a full description of PM task characteristics). The initial step toward understanding multitasking failures was therefore to investigate the brain regions involved in PM tasks as indicated by functional imaging. In the first study, Burgess et al. (2001) used PET to investigate regional cerebral blood flow changes in eight participants performing four different tasks, each under three conditions. The first condition (baseline) was subject-paced, and consisted of making judgments about two objects appearing together (e.g. which of two digits is the largest, or which of two letters comes nearer the start of the alphabet). The second condition consisted of the baseline task, but subjects were also told that if a particular combination of stimuli appeared (e.g. two vowels, two even numbers) they were to respond in a different way (press a particular key combination). However, in this condition (expectation) none of these stimuli actually appeared. In the third condition participants were given the same instructions and stimuli as in the first, except that the expected PM stimuli did occur (after a delay, and on 20% of trials), and participants had the chance to respond to them ("execution" condition). In the terminology of prospective memory researchers, the last two conditions were PM conditions in that they involved a delayed intention (see Burgess et al. 2001 for an outline of the further characteristics of PM tasks).

Relative to the baseline condition, rCBF increases across the four tasks were seen in the frontal pole (BA 10) bilaterally when the participants were expecting to see a stimulus, even though it did not occur. There were no further increases in this region when the intention cues were seen and acted upon. This result corresponded well with that of Okuda et al. (1998), who were the first people to demonstrate a role for BA 10 in prospective memory using functional imaging. Thus there seems to be both within- and cross-method support for a role of BA 10 in PM functions. And the Burgess et al. (2001) study suggests that this role is material and stimulus nonspecific, and probably involved more with maintenance than execution of the delayed intention.

However, one possible explanation for the Burgess et al. (2001) findings is that the activations seen in the expectation condition could be due to task difficulty or increased stimulus processing demands rather than anything to do with delayed intentions *per se*. This hypothesis was examined in a second PET experiment (Burgess et al. 2003). Three different tasks were administered under four conditions: baseline simple RT; attention-demanding ongoing task only; ongoing task plus "unpracticed" delayed intention (i.e. the first block of this condition); ongoing task plus "practiced" delayed intention (i.e. the second block of this condition). Under prospective memory conditions, Burgess et al. (2003) found significant rCBF decreases in the superior medial aspects of the rostral prefrontal cortex (BA 10) relative to the baseline or ongoing task only conditions. However, more lateral aspects of area 10 (plus the medio-dorsal thalamus) showed the opposite pattern, with rCBF increases in the prospective memory conditions relative to the other conditions, with lowest rCBF in the ongoing task . These patterns were broadly replicated over all three tasks. Since both the medial and lateral rostral regions showed (a) instances where rCBF was higher in a *less* effortful condition (as estimated by RTs and error rates), and (b) there was no correlation between rCBF and RT durations or number of errors in these regions, a simple task difficulty explanation of the rCBF changes in the rostral aspects of the frontal lobes during PM tasks was rejected. Instead, the favored explanation concentrated upon the particular processing demands made by these situations irrespective of the precise stimuli used or the exact nature of the intention, in particular the requirement to hold a thought in mind (i.e. stimulus-independent thought) whilst carrying out other operations on the presented stimuli.

Constraints for theorizing about the role of rostral PFC in cognition

The data that we have reviewed so far provide some constraints on theorizing about the functions of rostral PFC. Specifically, we will take the phenomena listed in Table 9.1 as a bare minimum of those for which a theory of rostral PFC function should account. The list is however: (a) far from being a complete summary of the findings that need to be explained; (b) partisan in that it favors findings from our own lab and emphasises results, which show relative medial/lateral differences; and (c) a somewhat unrealistic view in that it ignores concomitant changes in other brain regions, which may be theoretically instructive. One also needs to make the caveat, in considering the imaging findings, that in most neuroimaging experiments stimuli are presented visually, with responses made manually or verbally. Thus the relationship with situations using other stimuli/response forms is not well-established.

Bearing in mind these caveats, however, we will proceed with the currently available evidence (or at least the evidence of which we are aware: we would be very interested in hearing from researchers who have further evidence which can add to, or modify the content of this list, or the supporting citations). Please note that for the sake of completeness, findings FI(g), (o), and (p) are included in Table 9.2, even though they actually emerged from our testing of the theory, which was originally derived with the other constraints listed in Table 9.2 in mind.

Implications of these constraints

Human lesion (HL) study point (A) removes the possibility that rostral PFC plays a *critical* role in the over-learned cognitive processing of specialized

Table 9.1 Constraints for theorizing about rostral PFC function derived from human lesion (HL) studies

A. Rostral PFC lesions need not markedly impair performance on standard tests of intelligence, especially those that measure “crystallized” intelligence (e.g. Burgess, 2000; Goel & Grafman, 2000; Shallice & Burgess, 1991a), or those involving the use of over-learned procedures (e.g. arithmetic).

B. Rostral PFC lesions need not impair simple episodic memory functions such as forced-choice recognition (Burgess, 2000; Goel & Grafman, 2000; Burgess, Veitch, & Costello, submitted).

C. Medial rostral PFC lesions need not cause impairments on “Theory of Mind” tasks (Bird et al. 2004).

D. Rostral PFC lesions do not necessarily cause impairments on many (structured) traditional tests of executive function, such as the Tower of London test (Shallice, 1982), Stroop paradigms, WCST, Verbal Fluency (e.g. Burgess, 2000; Goel & Grafman, 2000). Importantly however, people with lesions that *include* rostral damage but also extend elsewhere may often show impairments on some of these tests (and others), e.g. Burgess, Veitch, & Costello, submitted; Stuss et al. 1998, 2000).

E. However it seems likely that rostral PFC lesions *do* cause disruption of episodic memory functions, which have a high meta-cognitive component (see Burgess & Shallice, 1996), such as initial learning of complex rules (Alexander, Stuss, & Fansabedian, 2003; Burgess, Veitch, & Costello, submitted; see also Strange et al. 2001 for congruent findings from functional imaging), and abnormal priming and false positive effects (e.g. Metzler & Parkin, 2000).

F. Rostral PFC lesions disproportionately impair performance in “ill-structured” situations (e.g. Burgess et al. 2001; Goel & Grafman, 2000; Grafman, 2002). In other words where the optimal way of behaving is not precisely signalled by the situation, so one has to impose one’s own structure.

G. Rostral PFC lesions impair multitasking, both in the laboratory and in everyday life (e.g. Burgess et al. 1998, 2000; Burgess, Veitch, & Costello, submitted).

systems (e.g. semantic memory, calculation, reading), and HL(D) suggests that rostral PFC processes are not critical for dealing with novel situations where performance parameters are easily determined, for example, where the demands of the task are well-specified by the task instructions, and moment-by-moment feedback occurs (in the sense that it is quite obvious when one has made a mistake, or is performing poorly). The corollary is given by findings HL(F) and HL(G): Rostral PFC would seem to be most involved in situations for which there is not a well-rehearsed or well-specified way of behaving, and therefore where behavioral organization needs to be self-determined. These points support the suggestion of Dreher et al. (2002), on grounds of functional imaging data, of a posterior-to-anterior organization of PFC as tasks become more “endogenously guided.” They also need to be balanced alongside the functional imaging (FI) finding (e), which argues

Table 9.2 Constraints for theorizing about rostral PFC (area 10) function from functional brain imaging (FI)

Rostral PFC

a Is not sensitive to the precise nature of stimuli (e.g. whether they are words, numbers, shapes, etc., see, for example, Burgess et al. 2001, 2003).
b Is not sensitive to the precise nature of intended action (in prospective memory tasks, see Burgess et al. 2001, 2003).
c Is not sensitive to precise response method (Burgess et al. 2001, 2003).
d Is consistently implicated in tasks where one has to "bear something in mind" whilst doing something else, for example, voluntary task switching after a delay (e.g. Koechlin et al. 1999), prospective memory (Burgess et al. 2001, 2003; Okuda et al. 1998), and "monitoring" type tasks (e.g. MacLeod et al., 1998).
e Haemodynamic changes in rostral PFC occur in a very wide variety of situations (e.g. Burgess et al. in press; Grady, 1999; MacLeod et al. 1998)
f Rostral PFC activations are not necessarily concomitant with recognizing experienced events (Burgess et al. in press; Herron, Henson, & Rugg, 2004).
g But do occur when one is remembering the thoughts one had about those events (Simons et al. in press a; in press b).
h Activation in rostral PFC regions may be unrelated to "task difficulty," at least as it is indexed by changes in RTs and errors on a task (Burgess, Scott, & Frith, 2003; Gilbert et al. in press).

Lateral Rostral

i Lateral rostral regional cerebral blood flow (rCBF) increases can occur when targets are expected but not actually experienced (Burgess, Quayle, & Frith, 2001).
j Lateral rostral PFC is sensitive to target frequencies or distributions (Herron et al. 2004; Okuda et al. in preparation).
k Lateral rostral regions show increased activation in situations requiring the recollection or manipulation of the products of previous processing (Burgess, Dumontheil, Gilbert, Simons, & Frith, in preparation; Christoff et al. 2003; Simons et al. in press a, in press b).

Medial Rostral

l Medial rostral regions do *not* show easily predictable blood oxygen dependent (BOLD) responses to routinization or practice (Burgess, Scott, & Frith, 2003).
m Medial rostral regions often show decreased activation in conditions that require goal-directed thought (Raichle, 1998; Raichle et al. 2001)
n Medial rostral regions show BOLD increases associated with attending to stimuli in the external world (Janata et al. 2002; Small et al. 2003).
o Medial rostral regions show BOLD increases when participants are viewing stimuli rather than imagining them (Gilbert, Frith, & Burgess, in press).
p Medial rostral regions (relative to lateral rostral regions) show activations in conditions which require attention to external stimuli but "shallow" processing of them (Burgess, Dumontheil, Gilbert, Simons, & Frith, in preparation; Gilbert, Frith, & Burgess, in press; Gilbert, Simons, Frith, & Burgess, submitted).
q Some medial rostral regions may show BOLD increases in a variety of situations that require stimulus-provoked introspection, such as recalling past thoughts one had about a stimulus when re-presented with it, or even thinking about the future when prompted to (Okuda et al. 2003; Simons et al. in press a, in press b; see also Zysset et al. 2002).

against a very task-specific interpretation (although there will be specific tasks which stress the processes supported by rostral PFC). This suggests that "rostral processes" (as we will refer to the cognitive processes, which are supported at least in part by the anterior parts of the PFC) operate at a "meta-representational" level, in other words are not tied tightly to one form or domain of representation (e.g. words, numbers, shapes, faces, actions, etc.). Support for this view comes also from findings HL(E), FI(a), (b), (c), (i), (l) and (m).

Thus the characterization of the rostral processing system as cross-domain (Burgess et al. 2003) and serving the purpose of guiding behavior in situations where the optimal course of action is not obvious or established (Burgess, 2000; Goel & Grafman, 2000; Pollman, 2004) seems secure. This view is consistent with both that of Fletcher & Henson (2001) and Christoff and colleagues (e.g. Christoff, Ream, Geddes, & Gabrieli, 2003). Fletcher and Henson echo the suggestion by McIntosh (1999) that the role of BA 10 in cognition is governed by its interactions with anatomically related regions. More specifically, they suggest that anterior PFC controls ventrolateral PFC (VLPFC) and dorsolateral PFC (DLPFC) processes, and that its role is to select between processes or goals: "if VLPFC and DLPFC form a functional unit concerned with updating/maintenance and selection/manipulation/monitoring, respectively, then perhaps controlling influences from AFC (anterior frontal cortex) regions enable optimal switching between these processes in order to maximise task performance." (p. 876).

It is important to note at this stage that these views contain strong implicit views of how the cognitive system might operate, or be organized. Thus, there is the inherent assumption that some brain processing is "stimulus-independent" (and therefore that some is stimulus-dependent). This is an important distinction, which is adopted in the forthcoming characterization of rostral PFC processes.

Findings HL(B) and HL(C) together make it unlikely, however, that the role of rostral PFC is simply to support the "tonic" or "steady" state of either stimulus-oriented (SOT) or stimulus-independent thought (SIT), because lesions in this area need not impair performance on simple forced-choice recognition or Theory of Mind tasks: the former are by definition stimulus-oriented in form and "theory of mind" tasks require some component of stimulus-independent thought in that one has to consider possibilities not directly signalled by the current stimuli (see also finding FI(f)). Nevertheless, Findings FI(n), (o), and (p) do suggest that, in a number of situations, medial rostral PFC can be involved in stimulus-oriented (as contrasted with *goal-directed*) processing. Furthermore, finding FI(d) could be interpreted as suggesting a role for rostral PFC, especially for lateral BA 10, in stimulus-independent thought, since these experiments require subjects to maintain a thought in the face of potentially competing stimuli.

One possible resolution that potentially fits these findings obtains in particular from the situations provoking finding FI(d), but also HL(F) and (G). These are nonroutine situations, where one has to formulate a way of behaving, or "create a new schema" in the terminology of the Shallice and Burgess model, beyond that directly signalled by the stimuli (see Burgess, 1997 for an outline of the role of novelty in executive function). It was therefore at this point that our thinking turned to investigating formally the possible role of rostral PFC in the contrast between stimulus-independent and stimulus-oriented thought, and the switching between these states specifically in novel situations. These investigations led to findings FI (g), (h), (j), (k), (o), (p), and (q). We will now outline the general specification of the hypothesis that spawned these investigations, and then the empirical evidence used to test it.

The gateway hypothesis: model specification

Basic assumptions

We make three basic assumptions, which should be fairly uncontroversial for most cognitive neuroscientists. (1) At an information processing level, the cognitive system is composed of modules specialized for certain functions. (2) The cognitive system is arranged as a functional hierarchy for much complex novel behavior, that is, that process A operates upon the products of the previously active process B. (3) "Thought" (i.e. the instantiation of mental representations) may occur without influence from neuronal activity provoked directly by stimuli external to the body.

Given these assumptions, we then adopt the general information processing framework outlined by Norman & Shallice (1980, 1986), and later expanded by Shallice and colleagues (e.g. Burgess et al. 2000; Shallice, 1988, 2002; Shallice & Burgess, 1991b, 1993, 1996; Stuss, Shallice, Alexander, & Picton, 1995).

A full description of this well-established theoretical framework is beyond the scope of the present chapter. However in brief, Shallice's Supervisory Attentional System theory is concerned with the role of the frontal lobes in the allocation of processing resources (Shallice, 1988) and describes a theory of behavioral organization and adaptation. There are four levels of increasing organization in this theory. The first level consists of "cognitive or action units," which correspond to basic abilities (e.g. reaching for an object, reading a word). The second level consists of "schemata." These are nests of cognitive or action units that have come to be closely associated through repetition. The third level is a process called "contention scheduling." This is the basic triggering interface between incoming stimuli, including thoughts, and the schemata. Its purpose is to effect the quick selection of routine behaviors in well-known situations. However of course many situations (or aspects of them) that we encounter are not well rehearsed. In this situation one has to decide consciously what one has to do. The cognitive system that effects this conscious deliberation is referred to as the "supervisory attentional system" (SAS), and processing critical to the function of this capacity is thought to be underpinned by structures in the PFC. More recent work has attempted to provide a finer level of specification of this model (Burgess et al. 2000; Shallice, 2002; Shallice & Burgess, 1996, 1998; Stuss et al. 1995).

The account developed below expands upon this model, by supposing that the information processing system supported at least in part by rostral PFC effects the biasing of the schemata operated upon by the contention scheduling process in two ways: (a) by biasing the relative activation of schemata in these situations of low triggering input and also (b) by increasing the relative activation levels of schemata which are not currently receiving input via sensory input systems, in accordance with a higher-level goal representation. Thus the overall function of the system is to enable mental behavior in situations where (1) no schema is sufficiently triggered by incoming stimuli (e.g. because there is no established way of behaving, the stimulus is entirely novel, or activation levels have reached asymptote) or (2) too many schema are being simultaneously activated (e.g. in a very difficult complex situation, or one where there are very many possible established behaviors without an obvious advantage to one of them).

The gateway hypothesis: specific proposals

In this way, we suggest that rostral PFC plays a role in the goal-directed *co-ordination* of SIT and SOT in situations where the established or predominant way of behaving would not achieve optimal outcome.

The stimulus-oriented and stimulus-independent distinction

All cognition can be classified as either stimulus-oriented, stimulus-independent, or more commonly perhaps, a combination of the two (often working together in different phases). By stimulus-oriented, we mean either *provoked by* something being experienced through the senses, or *oriented toward* something to be experienced through the senses. Examples of stimulus-provoked cognition are obvious (e.g. reading). Stimulus-oriented cognition is where one's attention is oriented toward input from the senses (or one of them), but there is an absence of the stimulus itself (e.g. a state of "watchfulness" or "readiness"). The precise relationship between stimulus-provoked and stimulus-oriented cognition is a moot point. But to simplify terminology, in the foregoing argument we will use the more general term "stimulus-oriented" to refer to any cognition, which is provoked by or oriented toward stimuli external to the body. This form can be contrasted with stimulus-independent thought, which is any cognition that has not been provoked by, or directed toward, an external stimulus. An obvious example is daydreaming or "zoning-out," but one might also include some forms of unprovoked rumination, introspection, or creative thought and the like.

As already stated, many examples of cognition lasting more than a few milliseconds will include aspects of both stimulus-oriented and stimulus-independent thought. For instance, remembering, in response to a question, a complex autobiographical event that occurred some time ago has aspects of stimulus-oriented cognition in that it is provoked by the stimulus question and is oriented toward that stimulus (e.g. to answer the question). Yet it also has a stimulus-independent component (the actual reconstruction of the memory; see Burgess & Shallice, 1996). In this way, it is most helpful perhaps to see these *in practice* as classificatory dimensions rather than absolutes.

Since there is only one set of central cognitive representations, there will be continuous attentional competition between SIT and SOT for activation of those representations. In many situations the relative attentional bias is determined automatically. For instance, a sudden unexpected stimulus will naturally "capture" attention, as would an expected stimulus congruent with the currently active goals which has a strong S–R relation (i.e. a sum if one were performing a mental arithmetic test). However in the absence of external stimulus, or where monotony has been achieved, SIT will tend to dominate (e.g. one's "mind will tend to wander"). SIT should also dominate when it is not obvious how one should behave (e.g. "ill-structured" situations); or where cognitive capacity has been exceeded to the point where behavior starts to break down (e.g. one starts to notice a large number of errors and ruminative (i.e. self-generated) thoughts ensue).

As a first hypothesis, for the sake of parsimony, we do not suppose that rostral PFC plays any direct part in the actual information transformations involved in either stimulus-independent or oriented thought, but merely acts as a routing system, determining whether it is the outputs of current (internal) processing or input from currently available (new) stimuli, which will be the focus of further processing by the cognitive system. A simple analogy might be a railway track switch-point, where we imagine the train as representing packets of information within the brain, and the tracks as the pathways that carry that information. The switch-point will have no influence upon the train itself (i.e. does not effect an information transformation), but merely determines the direction of the flow. In this analogy, one "track" governed by the switch-point may lead back to the specialist regions from which the information came, and another governs the flow of information to and from basic input/output systems (e.g. visual processing, motor effector systems, speech and language systems, etc.) via central representations.

In a model of this type, there would be competition for activation of central representations between the two pathways (i.e. either input to central representations from more basic systems or reciprocal activation from currently active central representations), and much of cognition could occur naturally through this competition without influence from the processes supported by rostral PFC (including much "thought," for example, that required to generate a new plan, solve a crossword problem, etc.). It would only be when either one pathway needs to be consistently *biased*, or when there needs to be rapid switching between the bias of the two that influence from the "switch-point" would be needed (see Figure 9.2). This biasing would typically occur in situations that are novel or where a specific demand for it has been determined (e.g. "I must pay special attention to . . ."; "I must think about . . ."). It will also

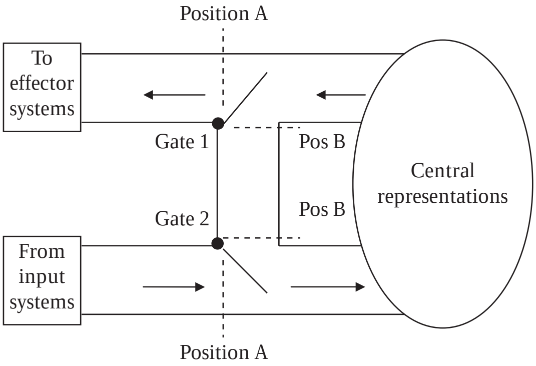

Fig. 9.2 Stylised representation of the "Gateway Hypothesis, Version 1.1" of rostral prefrontal function. Rostral regions are hypothesised to support a system, which biases the flow of information between basic systems and central representations (i.e. is equivalent to the adjustment of the position of the "Gates"). The gates are shown in the neutral position (= bias freely determined by context). If both gates are at position A, stimulus-independent thought is favored. If both gates are at position B, full engagement with (external) stimuli is effected. Other combinations have further experiential correlates, especially when one considers dynamic, moment-by-moment switching: part of the purpose of the diagram is to make the point that even a very simple switch system could effect a range of mental activity.

be used in spontaneous solution generation—perhaps, for example, the unprovoked thought "is there a better way of doing this?". In this way, this system is an important component of the "supervisory attentional system" (Shallice & Burgess, 1996). We assume, however, that much of the actual processing required in novel situations to determine a new course of action requires the additional operation of other prefrontal control systems (and the systems they control).

Direct empirical support for the gateway hypothesis

We have recently conducted a series of experiments, which lend support to this overall framework. These studies consistently find that areas of rostral PFC are involved in co-ordinating attention between externally-presented and internally-represented information.

Experiment 1: Evidence for the involvement of rostral PFC in switching between stimulus-independent and stimulus-oriented thought.
Gilbert, Frith, and Burgess (in press) asked subjects to perform three separate tasks in two conditions whilst undergoing functional magnetic resonance imaging (fMRI). In one condition subjects had to respond to stimuli presented visually, in the other subjects had to do the same tasks "in their heads." In task A, subjects tapped a response button in time with a visually-presented clock, or ignored the visual display (which now presented distracting information) and continued to tap at the same rate as before. Task B required subjects to navigate around the edge of a visually-presented shape, or to imagine the same shape and continue navigating as before. In task C, subjects performed a classification task on letters of the alphabet that followed a regular sequence. They either classified visually-presented letters, or mentally continued the sequence and classified the letters that they generated internally. Thus all three tasks alternated between phases where subjects attended to externally-presented information, and phases where they ignored this information and attended to internally-represented information instead. We investigated both the sustained neural activity that differed between two phases, and transient activity at the point of a switch between these two phases. Consistently, across all three tasks, medial rostral PFC exhibited sustained activity that differed between the two phases, in all three cases showing greater activity when subjects attended to externally-presented information. By contrast, right lateral rostral PFC exhibited transient activity when subjects switched between these phases, regardless of the direction of the switch (see Figure 9.3). This dissociation between medial and lateral rostral PFC regions was confirmed statistically in all three tasks. Thus, the results of the study strongly support the hypothesis

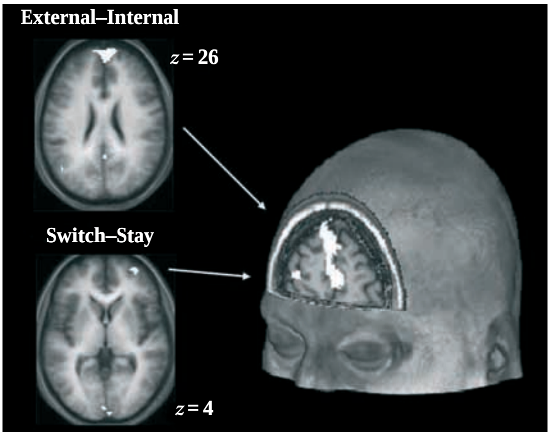

Fig. 9.3 Rostral brain regions identified as involved more in doing a task using stimuli one can currently see rather than doing the same task in one's head only (upper left-hand panel), and in switching between doing a task "in one's head" and doing the same task using stimuli one can currently see (the "Switch-Stay" contrast, lower panel).

that rostral PFC supports selection between externally- and internally-oriented cognitive processes, and suggest dissociable roles of medial and lateral rostral PFC in this selection process.

Experiment 2: Medial rostral PFC is most active in low demand attentional situations.

In a follow-up study (Gilbert, Simons, Frith, & Burgess, submitted), we replicated the finding of greater medial rostral PFC activity during attention to externally-presented versus internally-represented information. In addition, however, we found that activity in this region was correlated on a trial-by-trial basis with faster reaction times (i.e. a negative correlation) in a simple-reaction-time (SRT) baseline task. This finding is important for two reasons. First, it rules out an explanation of the activity we observe in medial rostral PFC in terms of "daydreaming" during simple tasks. If this were the case, greater medial rostral PFC activity (and hence the occurrence of daydreaming) would reflect disengagement from the baseline task, and should show a positive correlation with RT. Second, this finding helps to constrain theorizing on the functional role of this brain region. By demonstrating that rostral medial PFC activity correlates with better performance in a SRT baseline task, we can point to a task requiring focussed attention (in this case, focussed attention toward intermittent visual targets) to which medial rostral PFC makes a functional contribution (see also Stuss et al. 2005, for evidence from a human lesion study). Thus, contrary to the default mode hypothesis (Raichle, 1998; Raichle et al. 2001), it does not seem that any task requiring focussed attention will lead to "deactivation" of this area. Rather, we propose that this region plays a specific role in particular types of focussed attention tasks (i.e. deliberate biasing of attention toward externally-presented or internally-represented information), which it may also play during the state of conscious rest.

Experiment 3a and 3b: Evidence for the role of rostral PFC in stimulus-independent thought.

The suggestion from the studies of findings FI(d), (i) and (k) is that rostral PFC, especially lateral rostral PFC, plays a role in SIT. One example of a situation that involves SIT is where one is remembering the thoughts one had about a stimulus previously experienced (rather than the stimulus itself) or remembering other details of the context in which the stimulus was encountered. Simons, Owen, Fletcher, and Burgess (in press a) investigated this area of human cognition, with particular reference to understanding the anomaly that some functional imaging experiments of contextual recollection observed activation in BA 10 (e.g. Dobbins, Foley, Schacter, & Wagner, 2002; Rugg, Fletcher, Chua, & Dolan, 1999) whereas others did not (e.g. Henson, Shallice, & Dolan, 1999; Nyberg et al. 1996). One possible explanation is that the studies, which did find BA 10 activation involved recollecting which of two tasks was undertaken with target items: "task context," whereas the other studies focused on externally-derived features of context (e.g. recollecting the position on a monitor screen target items were presented: "position context").

Simons et al. (in press a) investigated the possibility that BA 10 might be differentially involved in recollecting internally-generated versus externally-derived contextual information by contrasting directly the recollection of task context and position context within participants. They observed a functional dissociation within rostral PFC, with lateral regions associated with recollection of both task- and position-based contextual details and a more medial region showing significantly greater activation during recollection of task context than position context. This lateral versus medial dissociation was apparent regardless of whether words or famous faces were being remembered, reinforcing the idea that the region is involved in central, stimulus-independent executive control processes (see findings FI(a)–(c)), and was unrelated to task difficulty as estimated by accuracy and reaction time. These findings show remarkable concordance with the regions identified as showing BOLD changes in prospective memory paradigms by Burgess et al. (2001, 2003; see Figure 9.4).

A follow-up study was conducted to contrast recollection of task context with another example of contextual detail—remembering the temporal context in which stimuli were presented (Simons, Gilbert, Owen, Fletcher, & Burgess, in press b). The principal results were very similar to those from

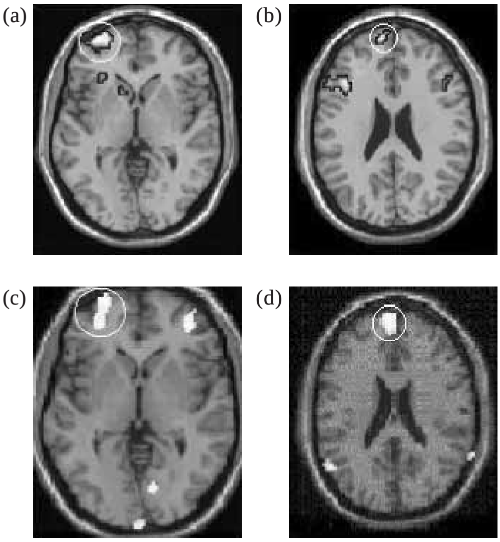

Fig. 9.4 Remarkable agreement between functional imaging method and study. Panels (a) and (b) show the rostral PFC regions identified as important for source memory using fMRI by Simons et al. (in press a). Panels (c) and (d) show the rostral brain regions identified as showing activation changes in prospective memory tasks using PET, by Burgess et al. (2001, 2003).

the previous experiment. Regions in lateral and medial rostral PFC were associated with significantly greater activation during task context than time context recollection. Just as before, the rostral PFC regions were not stimulus-specific, and were unrelated to task difficulty. An interesting further question concerned the stage of the retrieval process during which rostral PFC might be recruited: pre-retrieval cue specification or post-retrieval monitoring and verification, for example (Burgess & Shallice, 1997; Simons & Spiers, 2003). Simons et al. (in press b) addressed this question by presenting some retrieval cues (indicating whether the upcoming trial would involve task or time context recollection) on their own, without accompanying target stimuli. During such trials, which might be considered to involve pre-retrieval processes but no retrieval search or post-retrieval monitoring, significant activation was observed in the same lateral rostral PFC region that was associated with recollection of both task and time context, indicating that the role played by this region may be in pre-retrieval cue specification processes (see also Ranganath & Paller, 2000, for a similar view). Medial rostral PFC activation was not observed in this contrast, suggesting a role for this region in processes occurring after presentation of the target stimulus (e.g. relating to retrieval search or monitoring of retrieved information). This view was corroborated by evidence from timecourse analysis, in which activation in medial rostral PFC peaked significantly later than that in the more lateral region. In this way, the results echo strongly those of Gilbert et al. described above, in which activation in medial rostral PFC was also found to occur when coordinated attention between external stimuli and internal thoughts was required.

Experiment 4: Stimulus-oriented and stimulus-independent thought contrasted. In a fourth experiment (Burgess, Dumontheil, Gilbert, Simons, and Frith, in preparation) we aimed to contrast directly the conditions which in Experiment 2 we had found to provoke medial BA 10 activations (low-demand attention to external stimuli) with the suggestion from Experiments 3a and 3b that lateral rostral PFC is involved in stimulus-independent processing (see also Christoff et al. 2003). In this fMRI experiment, two different tasks (numerical or spatial) were administered under four conditions. The first was a simple RT attentional baseline (press the left/right button on alternate trials as fast as you can each time a stimulus appears). The second made the same attentional demands as condition 1, but also required some basic stimulus processing (e.g. "press the button on the side of the largest of two numbers"). The third condition made the same demands as conditions 1 and 2 but additionally introduced a requirement of processing self-generated information. For instance, for the numbers task, participants were asked if the sum of two numbers currently being presented to them was larger or smaller than the sum of the last two numbers presented. Clearly however, this condition not only makes demands on processing self-generated information, but also requires Ss to remember information from one display to another. Therefore we had a fourth condition, which was a control for these demands. For instance, in the numerical task, participants were asked if the number on the left of the screen was larger or smaller than the number on the left of the previous screen. The results were as predicted by the Gateway Hypothesis: an area of medial BA 10 was more active in condition 1 (basic attention to external stimuli, no stimulus processing) than in condition 3 (stimulus-independent thought) as previously discovered (see experiment 2). And an area of lateral rostral PFC was more active in condition 3 compared with condition two (stimulus processing). Overall, the brain region by condition interaction was significant at $p < .001$. Moreover, the lateral BA 10 finding could not be due to the "working memory" or rehearsal demands of the task, since activation in this region was significantly greater in condition 3 than in condition 4 (although we do not contend that rehearsal has no SIT component whatsoever).

The gateway hypothesis and the medial *vs*. lateral rostral PFC distinction

The results of this series of studies strongly support a role of rostral PFC in co-ordinating internally- and externally-oriented information. There is also strong evidence for functional dissociations between medial versus lateral rostral PFC across a number of tasks (see also Burgess et al. 2003; Koechlin et al. 2000).

However the precise operating dynamics of this system have yet to be determined. There are many possibilities that will need to be resolved both conceptually and experimentally. For instance we have characterized on the basis of our experiments a function of medial BA 10 as "biasing attention toward current sensory input," and that of lateral BA 10 as being concerned with "biasing attention toward internally generated thought." For the most part we have contrasted these two functions. Yet since the purpose of both is to modulate the activity of currently selected schemata, there seems no need to exclude the possibility that both "streams" could work in concert in some situations. It is possible to conceive of such situations, but this possibility remains largely untested. Another possible avenue of enquiry concerns the possible U–shaped function for rostral PFC function that emerges from our characterization. According to this hypothesis SIT could be provoked on the one hand by a lack of stimulating input (e.g. one's mind wandering whilst performing a monotonous task) or on the other by too much sensory input (e.g. performing a very difficult task where one is making mistakes and starts to ruminate on one's failures). There are many other fascinating dynamic aspects which also remain to be discovered.

Summary

This chapter presents a new information processing hypothesis of rostral PFC function, and some empirical supporting evidence. The framework makes a distinction between stimulus-oriented (i.e. provoked by, or directed toward) and stimulus-independent thought, and suggests that rostral PFC acts as a "gateway," which biases the priority of information from each stream. The strength of this hypothesis is that it is a framework that (a) makes a small number of assumptions; (b) makes predictions that are more readily testable empirically than alternative theories; and (c) introduces a potentially unifying explanation of the previous findings involving both medial and lateral rostral PFC that is independent of "task difficulty." The account is in this sense a synthesis of the excellent previous work by, in particular, Kalina Christoff, Etienne Koechlin, Marcus Raichle, Vinod Goel, Jordan Grafman, Chris Frith, Don Stuss, and their colleagues, using a simple proposal to explain how these quite different previous accounts might be linked. We do not, however, suppose that we have as yet achieved anything like a full specification of how the rostral PFC system works. Indeed, we have pointed out some aspects of our own data which whilst very broadly fitting the overall framework, nevertheless test our knowledge of the dynamics of the system in certain situations, in particular the exact relative roles of the medial and lateral rostral PFC regions. For this reason, the hypothesis presented here has been termed "version 1.1." We will update these versions as progress allows.

If the "gateway hypothesis" is correct, it makes interesting predictions about the potential involvement of this brain region in psychological or psychiatric disorders. Thus one might suppose that some forms of dysfunction of a mechanism of this kind might contribute to an inability to distinguish between one's thoughts and one's experiences, which could be a plausible partial account of hallucinatory phenomena in schizophrenia. Similarly for instance, an account using this framework could be constructed for symptoms linked to unwanted (intrusive) thoughts. These speculations remain to be tested. For the moment, we have attempted to address a critical issue for our understanding of how the brain operates, and do so taking full heed of Pat Rabbitt's sage words.

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