68 The Fractionation of Supervisory Control

TIM SHALLICE

ABSTRACT   Three different frameworks for understanding the functions of different regions of prefrontal cortex—working memory, general intelligence, the Supervisory System approach—are compared. Three different lines of neuropsychological evidence are discussed with respect to the third of these frameworks. The contrasting functions of the human left and right dorsolateral prefrontal cortex are then considered. The left is held to be involved in top-down strategic modulation of lower-level systems while the right is considered to be more concerned with the control of checking that on-going behaviour accords with task goals. Finally, the functions of anterior prefrontal cortex are assessed; it is argued that they are concerned with changes in cognitive mode, particularly when that involves the realization of previously set-up intentions.

Approaches to prefrontal cortex

It is standard to view the prefrontal cortex as the seat of a high-level system (or systems) that receives input from more specific lower-level systems and that in turn modulates or controls the operation of the lower-level systems (e.g., Shallice, 1982; Goldman-Rakic, 1987). The prefrontal cortex is internally highly complex, with major functional differences between the lateral, orbital, and medial surfaces, along with increasing abstraction of function as one moves toward the frontal pole. Historically, however, the most deeply investigated region has been the dorsolateral region. The operation of these regions has been viewed within a number of different conceptual frameworks. This chapter considers these various frameworks.

THE WORKING MEMORY APPROACH   The best-known framework is the working memory framework, which stemmed initially from Jacobsen's (1935) findings of a delayed response deficit in monkeys with frontal lobe lesions. The working memory framework became the dominant conceptual framework when it was shown with single-cell recordings that many units in dorsolateral prefrontal cortex (DLPFC) remained active during the delay (e.g., Fuster and Alexander, 1971). This approach was broadened by Goldman-Rakic (1987), who argued that a more dorsal area

TIM SHALLICE   Institute of Cognitive Neuroscience, University College London, London, U.K.

around sulcus principalis is the seat of spatial working memory, but a more inferior area on the lateral surface holds working memories for the identity of stimuli.

Which operations related to working memory might be affected by prefrontal lesions? First, it should be noted that in the delayed response tasks, a deficit occurs with only one spatial position having to be held. Yet the capacity for spatial span—the ability to reproduce without delay a string of spatial positions by pointing—is about six positions in humans, and dramatic loss of capacity is typically found following right parietal lesions in humans (De Renzi and Nichelli, 1975). Indeed, patients with prefrontal lesions often are not impaired on spatial span tasks. Thus, patients with prefrontal lesions in a study reported by Owen and colleagues (1990) were impaired when spatial information had to be used in a more complex way, but they were unimpaired on spatial span per se. Therefore, damage to DLPFC lesions does not appear to impair the short-term spatial memory store. Possibly it affects the maintenance of spatial attention.

The situation is similar for verbal span. Rypma and D'Esposito (1999) found that on a verbal span task, activation of DLPFC became greater only when six items rather than two were being processed while the information was encoded, and load had no effect during the delay period. Instead, changes in memory load affected activation of parietal cortex during the delay. Moreover, patients with highly selective impairments of verbal span are typically found to have left parietotemporal lesions (Warrington and Shallice, 1969; Shallice and Vallar, 1990). Thus, the processing carried out in DLPFC would seem to be primarily concerned with activities other than the mere retention of information in working memory, which is the responsibility of parietotemporal cortex.

A dramatic demonstration that area 9/46 is involved in operations rather than storage per se can be found in the neuroimaging study reported by Rowe and colleagues (2000) (figure 68.1). In this study, maintenance of information in working memory was associated with bilateral activation of Brodmann's area (BA) 8 and of the parietal cortex. The critical mid-dorsolateral area (area 9/46) was activated only when the information being held in working memory was
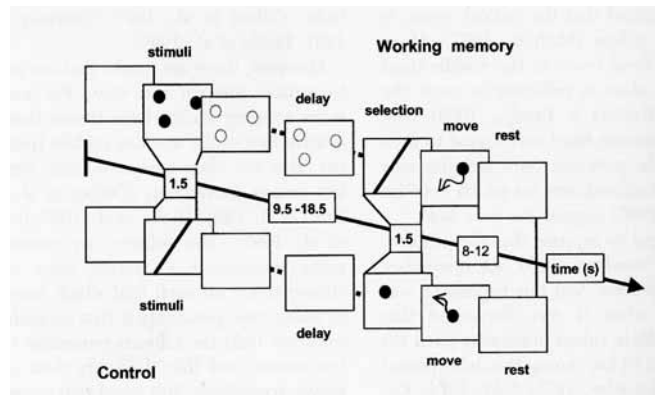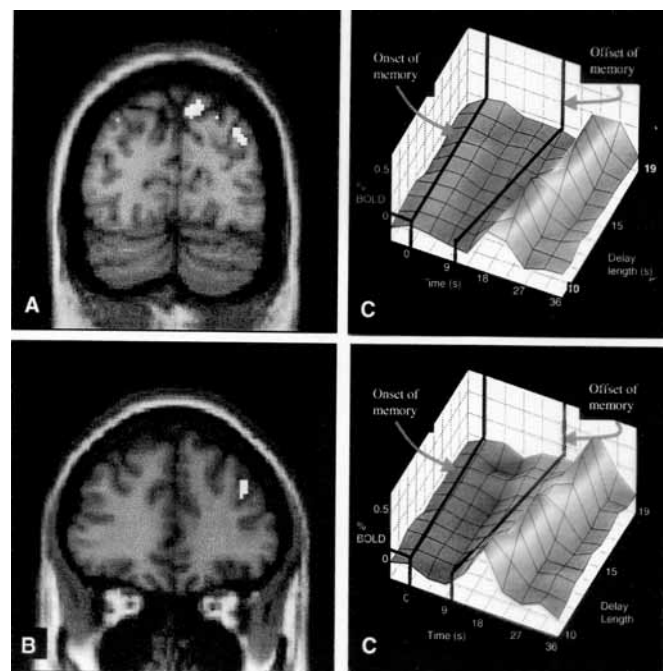
943

FIGURE 68.1   In a study reported by Rowe and colleagues (2000), subjects had to hold in working memory the position of three dots for a variable length of time. At the end of the delay interval, a line that went through only one of the dots came on. The subjects had to point to where on the line there had been a dot. Area 9/46

activation was associated with the offset operation (*B*) and not with the maintenance of information over the delay (*A*). *C* illustrates when during the time-course at the trial (*x*-axis) activation (*z*-axis) occured for trial of different length (*y*-axis). (See color plate 47.)

used to effect the response. Thus, DLPFC appears to be involved in cognitive operations rather than storage.

DORSOLATERAL PREFRONTAL CORTEX AS THE SEAT OF 'G'   A second conceptual framework holds that the critical function being effected by DLPFC is linked to working memory but also holds that it has a much more complex content than have the buffers being used to store spatial information. Duncan and colleagues (2000) have argued that the lateral prefrontal cortex contains highly adaptive cells that form the seat of general intelligence, designated *g*. They introduced three main lines of evidence. First, many of the cells in this region adapt their triggering features very flexibly to the specific task (Duncan and Miller, 2002). Second, Duncan and Owen (2000) performed a meta-analysis of functional imaging studies each of which examined a single variable related to the following factors: task novelty, response competition, working memory load, working memory delay, and perceptual difficulty. They compared activations for all pairs of conditions that differed on only one of the dimensions; for instance, a condition with response competition was contrasted to one without it but that was otherwise identical. They found that in regard to anterior structures, the maxima all lay in the anterior cingulate cortex and in a swathe down the two lateral prefrontal cortices. More specifically, this second set of maxima was thought to be clustered around the middle and posterior part of the inferior frontal sulcus

(IFS) and more ventrally along the frontal operculum. Critically, however, the five different types of contrast did not localize differentially within these regions. The areas of activation all overlapped. The third line of evidence came from a functional imaging experiment that contrasted three types of task that loaded heavily on *g* but otherwise had no apparent structural (i.e., lower-level processes) in common. All were odd-one-out tests. However, one was of shapes, the second was of relations between letters in a string, and the third involved spatial relations. When each of the three was compared with a structurally similar task that loaded much less on *g*, they all significantly activated the lateral prefrontal cortex (figure 68.2).

Duncan (2001) has drawn an analogy between the functional role of this region and the working memory of a production system model called SOAR (Newell, 1990). Production systems are artificial intelligence systems that have operations based on productions. These are condition-action pairs: when the conditions of a production are satisfied by perceptual representations or representations currently in working memory, then an action occurs, which can be an output or a new input to working memory. SOAR is one of the two symbolic models that have been most used to simulate in detail a wide range of cognitive processes. Its working memory contains elements that represent states of the environment, elements that correspond to its goals at various different levels, and elements that correspond to the
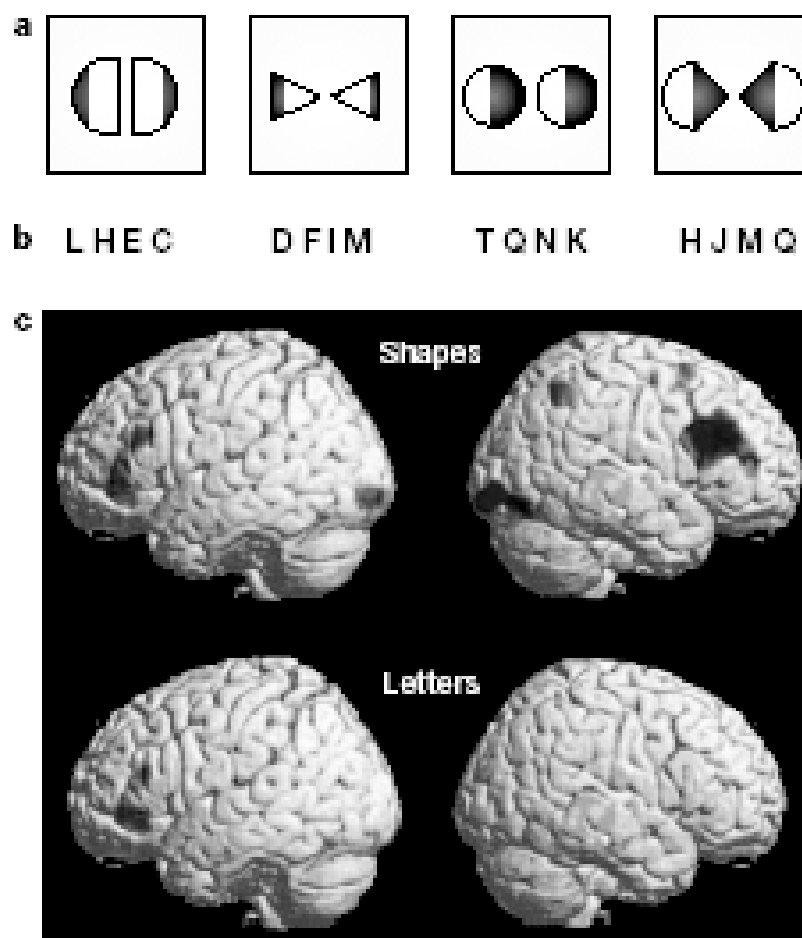
944   HIGHER COGNITIVE FUNCTIONS

FIGURE 68.2 Demonstration by Duncan and colleagues (2000) of an association of DLPFC activation with general intelligence (g) processes. (a–c) The activation differences between carrying out the IQ tasks, compared with performing cognitively undemanding control tasks using similar stimuli. The three tasks involved shapes, letters, and spatial relations. (See color plate 48.)

working memory outputs of previously executed productions. Thus, this approach can be related to the previous one, but it greatly broadens the concept of what the contents of the active working memory contain.

Duncan's approach makes two strong challenges. First, in principle, it allows one to characterize how much individual tasks would require a higher-level system, in that one could specify how much demand they would make on SOAR's working memory. Second, and much more controversially, it views the lateral prefrontal cortex as having a unitary function, if a very broad and abstract one.

THE SUPERVISORY SYSTEM APPROACH   Although the SOAR analogy could in principle be used to assess how much individual tasks require a high-level control system, in practice SOAR has proved to be an inadequate model of human cognition (Cooper and Shallice, 1995). Computationally, the most interesting aspect of SOAR, and what made it superior to earlier symbolic models of cognition, is that it makes a basic division between situations in which appropriate

actions can be routinely carried out and those in which the system cannot initially "decide" what to do, where it confronts an impasse. The system then uses special procedures to deal with the impasse and produce a plausible approach.

The third approach to lateral prefrontal (and also frontal pole) function makes qualitatively the same distinction, but the model is tailored to the specific requirements of a biological processor that modulates a variety of lower-level systems. This model views the prefrontal cortex as containing a Supervisory System that modulates a lower-level system of action and thought selection—known as contention scheduling (Norman and Shallice, 1986; Shallice and Burgess, 1996; figure 68.3). The basic functional division between Supervisory and non-Supervisory Systems echoes that in SOAR: contention scheduling implements routine actions. However, the successful carrying out of nonroutine actions is held to require the additional use of the Supervisory System. As with the SOAR framework, contention scheduling was also proposed to operate analogously to a production system. Production systems are placed in a
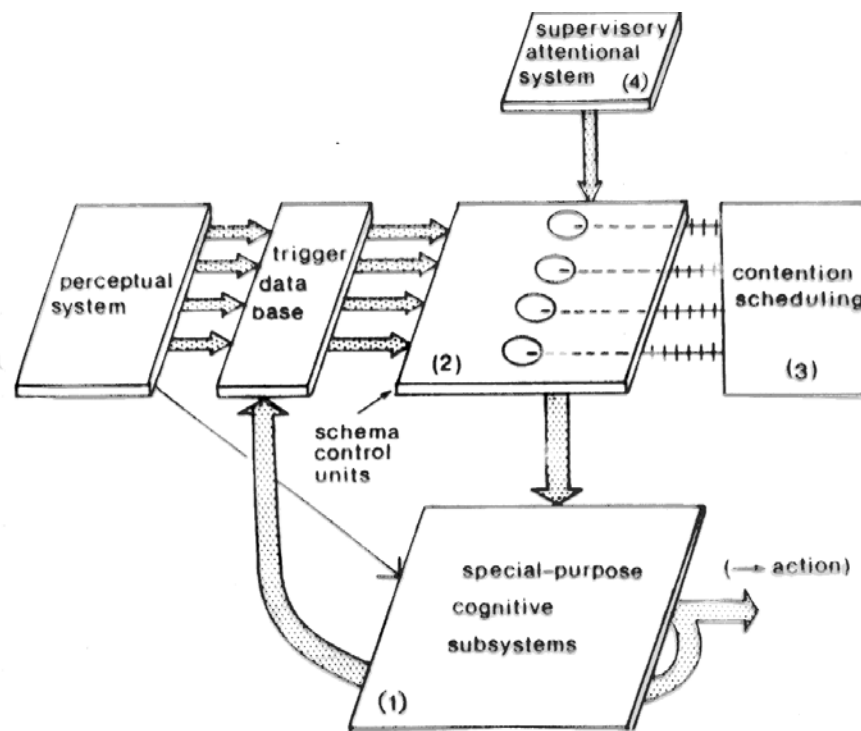
FIGURE 68.3   The original version of the Supervisory System model.

quandary when more than one production has its conditions satisfied at the same time. If all are executed, they may conflict with each other or remove each other's preconditions for selection. SOAR's impasse procedure is one way of dealing with the problem. In contention scheduling, a selection is made of which production (in our terminology, schema) will control the special-purpose processing systems it requires. This is based on McDermott and Forgy's (1978) approach to conflict resolution. Each schema has a salience measure, activation, and there is mutually inhibitory competition to determine which schema achieves an activation level that exceeds the selection threshold (see Cooper and Shallice, 2000, for an implemetation). This schema then operates by utilizing the processing subsystems it requires. This has similarities to the operation of the basal ganglia (see Gurney, Prescott, and Redgrave, 2001).

Evidence for the Supervisory System approach   Many different types of evidence support the idea that prefrontal cortex is involved in nonroutine as opposed to routine operations. These various lines of evidence include animal studies (e.g., Butter, 1964), neuropsychological studies (e.g., Shallice and Evans, 1978), electrophysiological studies (e.g., Knight, 1984), and functional imaging studies (e.g., Raichle et al., 1994; Jueptner et al., 1997).

More specifically, in the model, damage to the Supervisory System in prefrontal cortex leads to behavior controlled by contention scheduling. Behavior should then inevitably

be controlled by the schema that perceptual or working memory triggers, operating in an overlearned fashion, lead to be the strongest activated. Here we can consider three examples; the first two come from studies of neurological patients.

Della Malva and colleagues (1993) showed patients a series of cards that were either pictures (in one experiment) or words (in another). The cards told a story or made up a sentence, but were presented in a mixed-up order. Participants were asked to put the cards in order. There were two key conditions. In one, the original sequences contained a "capturing pair" of items in which two pictures (or words) appeared strongly associated but in fact represented very different stages of the story. Control subjects and patients with posterior lesions solved the two types of sequence equally well. By contrast, patients with anterior lesions were 15% worse if they had to overcome a capturing pair. The capturing pair triggers an overlearned thought schema in contention scheduling. It cannot be inhibited when the Supervisory System is damaged.

A more dramatic example was provided by Verin and colleagues (1993). Subjects were presented with two squares on a screen and had to guess which was correct. After the subject had guessed, the squares disappeared. At 15 s later, the squares reappeared, the subject guessed again, and so on. Which response was correct was dictated by a simple alternating sequence. Control subjects made an average of more than three errors before a sequence of ten correct

946   HIGHER COGNITIVE FUNCTIONS

responses. Patients with frontal lesions, however, made on average only 0.1 errors. They alternated spontaneously from trial 1. This can be explained if in contention scheduling the "move to nonrepeated target" is the dominant schema. This is plausible, as evinced by 6-year-old children showing the same behavior. It is unclear how a working memory or *g* account can explain this finding.

The third example used transanial magnetic stimulation (TMS). In a study reported by Jahanshahi and colleagues (1998), subjects attempted to generate a random string of single digits. As Baddeley (1986) showed, to produce a random string of numbers, subjects must inhibit the currently activated cognitive schema after each digit is produced. An unrelated schema must then be activated to produce the next digit. In the current framework, this process would require the inhibition of perceptual or memory triggers, and would therefore require a Supervisory System. Baddeley asked subjects to produce digits in time to the beat of a metronome. He showed that the degree of randomness declined as the rate of digit production increased. At the speed used by Jahanshahi and colleagues of one digit every 1.2 s, subjects frequently use the schemas of counting upward or downward in ones, the most routine procedure, or in twos, a somewhat less routine procedure. TMS over the left DLPFC increased the incidence of the most routine response, counting in ones, and decreased the rate of counting up or down in twos.

The internal organization of a Supervisory System

Three different lines of ideas support the view that higher-level modulating systems are not internally equipotential, as the *g* account claims. First, post-SOAR artificial intelligence systems that operate in nonroutine situations can require not just an all-purpose working memory in addition to productions, but a number of computationally quite distinct high-level processes (see Fox and Das, 2000).

Second, from the perspective of classical neurobiology, Petrides (1994) has argued that we need to distinguish between the functions of the ventrolateral prefrontal cortex (VLPFC) and DLPFC, but in a different way from Goldman-Rakic. VLPFC is held by Petrides to be involved in "active maintenance" operations, with the dorsolateral region being involved in "manipulation" operations. A series of experiments on spatial and verbal working memory using both PET and fMRI (see, e.g., Owen et al., 1999) have provided support for Petrides's position.

Third, functional imaging evidence now suggests that there is a set of distinct regions with putatively different cognitive functions in the lateral and anterior parts of prefrontal cortex. The evidence comes from a somewhat surprising source. Since the mid-1990s, some of the most frequently used functional imaging paradigms that give rise to pre-

frontal activations have been those involving episodic memory. It has been found that many different regions are activated in a large variety of different combinations according to the specific paradigm. Thus, Henson, Shallice, and Dolan (1999) and Rugg, Henson, and Robb (2003) consider the following regions to have different functional roles, or at least to be differently activated in a fairly consistent pattern across different type of episodic memory paradigm: left anterior, right anterior, and, in particular, left and right dorsolateral and left and right frontal operculum—both of which pairs appear to have different functions in the two hemispheres (see also Lepage et al., 2000; Fletcher and Henson, 2001).

Amnesic deficits do not occur following lesions to the frontal lobe, except most typically in the context of aneurysms of the anterior communicating artery on their posterior inferior medial surface, and most plausibly when the lesion involves the basal forebrain, which is a key structure for the cholinergic input to the hippocampus (Damasio et al., 1985). Lesions of the lateral surface do not generally give rise to problems of core memory processing. However, many episodic memory experiments require the subject to carry out, in addition to core memory operations, a series of other cognitive processes that tend to be similar for each test stimulus in a given condition. For instance, in a "source memory" experiment in which the subject must attempt to decide whether a test recognition stimulus that occurred earlier did so in the same or a somewhat different setting, complex cognitive operations as well as memory operations occur. Thus, it is plausible that most of the prefrontal regions activated realize different cognitive operations rather than specifically memory operations.

A first attempt to specify what the internal organization of a Supervisory System might be was made by Shallice and Burgess (1996; figure 68.4). A basic assumption of the model is that a key process in coping with a nonroutine situation is to develop and apply what would be termed phenomenologically an appropriate strategy. In terms of the model, a strategy corresponds to the operation of a schema (or set of schemas) in contention scheduling, which is activated above threshold only as a result of top-down output from the Supervisory System.

Lateralized dorsolateral functions

STRATEGY PRODUCTION AND EXECUTION   The basic set of ideas can be applied to the cognitive processes involved in episodic memory experiments. Thus, it has been known for many years that the optimum strategy for retaining a list containing related items is to produce an abstract structure that ties the items into a structured whole (Mandler, 1967). Participants standardly reorder the input items for rehearsal into subcategories when a list that contains them is presented in
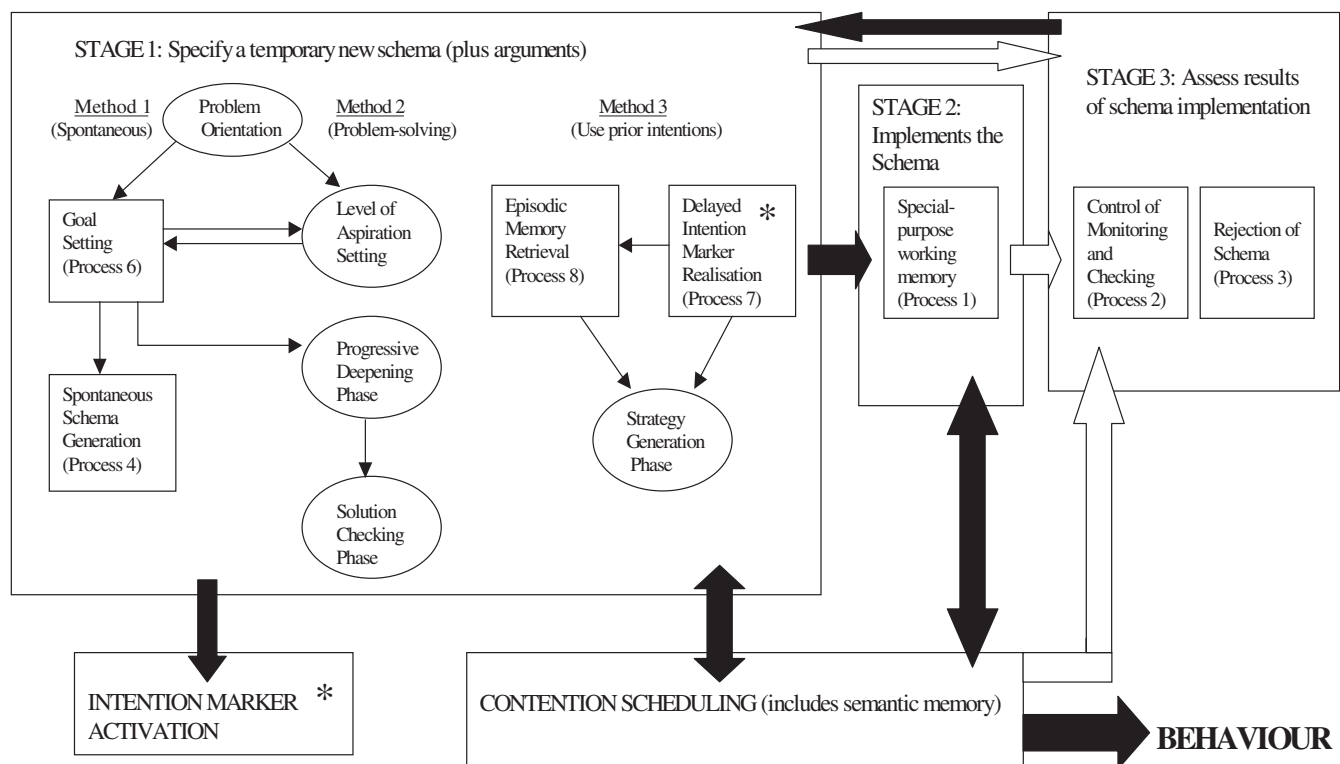
FIGURE 68.4   The Supervisory System component of the Mark II Supervisory System model of Shallice and Burgess (1996).

random order. Our group (Fletcher, Shallice, and Dolan, 1998) presented subjects auditorily with sets of 16 words each for 32 s. In each list, four words were drawn from each of four subcategories of the same broad semantic domain (e.g., for the domain food, there were four different meats, four kinds of fish, four breads, and four fruits). Subjects were given the sets of words in three different ways. The presentation order of the words could either be with each subcategory occurring in a block (procedure 1) or in one of two forms of random sequence, either with prior knowledge of what the subcategories are (procedure 2) or with no knowledge of it (procedure 3). In addition, we followed the argument of Moscovitch (1994) that a demanding secondary task would impair frontal executive processes, which was directly supported in an earlier study (Shallice et al., 1994). Thus, at the same time as listening to the lists, participants had to carry out a sensorimotor task involving moving a joystick to an indicated position. This involved otherwise identical input and output processes unrelated to those used in the memory encoding task. Two forms of this task differed in how easy it was for subjects to anticipate the next stimulus. In one case the sensorimotor task was completely predictable and in the other case it was random. The two sensorimotor task conditions were combined factorially with the three methods of list presentation to give six conditions in all.

Subjects underwent positron emission tomography (PET) as they encoded the lists. Later they were tested on how well they remembered them. The lists were equally well remembered in all conditions but one, in which the list structure was random and subjects were given no prior information as to the subcategories (procedure 3) *and* subjects had the demanding rather than the easy secondary task. In this condition, subjects recalled significantly less. Moreover, their recall was less well organized into categories. Subjects were not able to effectively use the strategy of organizing the words in the list into the four subcategories.

In only one region did the level of activation show a critical interaction of the secondary task with the list presentation procedure. This was a left dorsolateral area just above the IFS. There was a large effect of difficulty of distraction on the degree of activation in this region for procedure 3 but not for the other two procedures, mirroring its effect on the ability to produce a satisfactory organization for the list (figure 68.5). Thus, the creation and/or use of an appropriate strategy in the situation appeared to depend on a specific region of the left lateral prefrontal cortex. It might be objected that what was impaired in the critical condition was the ability to abstract, and not the ability to produce a strategy. But producing a strategy typically requires a participant to abstract over aspects of the situations where action has previously not been sufficiently successful. I will assume the two processes involve the same structures.

Reverting to a nonmemory domain, this result is analogous to the very different study of Jahanshahi and col-
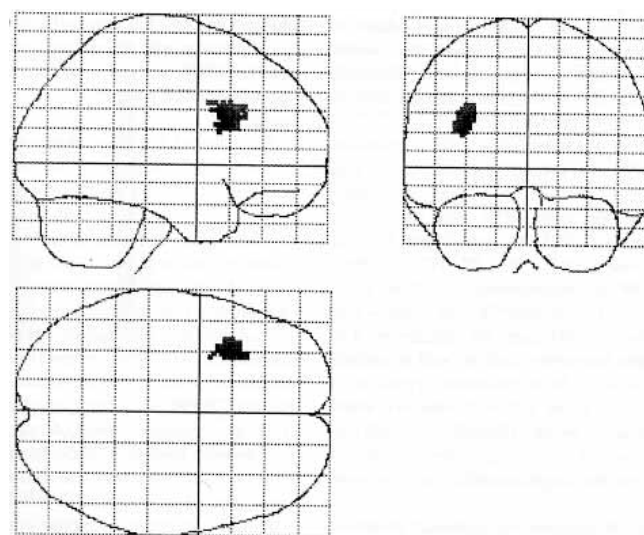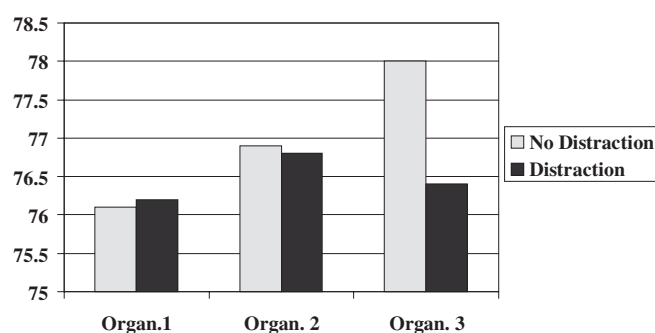
948   HIGHER COGNITIVE FUNCTIONS

FIGURE 68.5   Activations of a region of left DLPFC during the three different conditions of the memory organization study reported by Fletcher, Shallice, and Dolan (1998). (See color plate 49.)

leagues, in which it was only TMS of the left DLPFC that led to a greater relapse into routine behavior, and therefore left DLPFC could be presumed to be the region required in top-down activation of other schemas (for related ideas, see Frith, 2000; Braver, Cohen, and Barch, 2002). TMS of the right DLPFC did not produce an equivalent effect. fMRI findings led to a similar conclusion, namely, that the left dorsolateral region was the most critical area (Jahanshahi et al., 2000).

CHECKING STRATEGY EXECUTION IN NONROUTINE SITUATIONS An obvious objection to the claim that there is a degree of lateralization in the top-down modulation functions of prefrontal cortex is that in these experiments, lateralization occurs simply because of the material used. However, the right DLPFC has been selectively activated using the same material in other memory situations. For instance, one such study (Fletcher, Shallice, Frith, et al., 1998) was a complement to the encoding study just discussed. This study involved retrieving organized lists of words. Five minutes before scanning in the experimental, so-called internally cued condition, subjects were presented with an organized list, which, as in the previous study, contained four items each from four related subcategories. During PET, subjects received the stimulus "next" every 4 s and had to attempt to recall another word from the list. In the control, externally cued condition, there were 16 much more specific categories in each list, each with a different cue (e.g., for *nan*, the cue was *Indian bread*). A different cue was presented every 4 s at retrieval. In addition, two word repetition tasks acted as control tasks, one for each of the types of retrieval cue used in the two retrieval conditions. When results were compared with results on the corresponding repetition control condi-

tions, both retrieval tasks gave rise to significantly greater activation in a large region of the right frontal cortex. In complete contrast to the organization-at-encoding task, there were no effects in *left* prefrontal cortex.

This left-right contrast reflects the Hemisphere Encoding and Retrieval Asymmetry generalization of Tulving, Kapur, and Craik (1994) (see Cabeza and Nyberg, 2000; Lepage et al., 2000; Fletcher and Henson, 2001). However, in addition, there was an unexpected double dissociation in the activation produced within the right prefrontal cortex. In right DLPFC, internally cued recall gave rise to significantly greater activation than externally cued recall. By contrast, in the posterior ventral prefrontal cortex there was significantly greater activation in the externally cued condition, which involved paired associate recall (figure 68.6).

Neuropsychological evidence exists concerning the failure of the relevant process. Stuss and colleagues (1994) gave subjects lists of the same length as in our study—16 words—to remember. Indeed, some lists contained four subcategories, as in our procedure. The task was free recall. A group of patients with right prefrontal lesions and a second group of patients with left frontal lesions were compared with normal control subjects. Patients with left frontal lesions performed worse than the others on free recall. However, it was the result in the patients with right frontal lesions that was particularly relevant. This group, but not patients with left lesions, produced a significantly larger number of repeated items on the free recall protocols, more than double the rate of controls.

Why might these effects be associated with the right DLPFC? When dealing with novel situations, it is necessary to continuously check the appropriateness of the behavior to be produced. We therefore proposed that the process

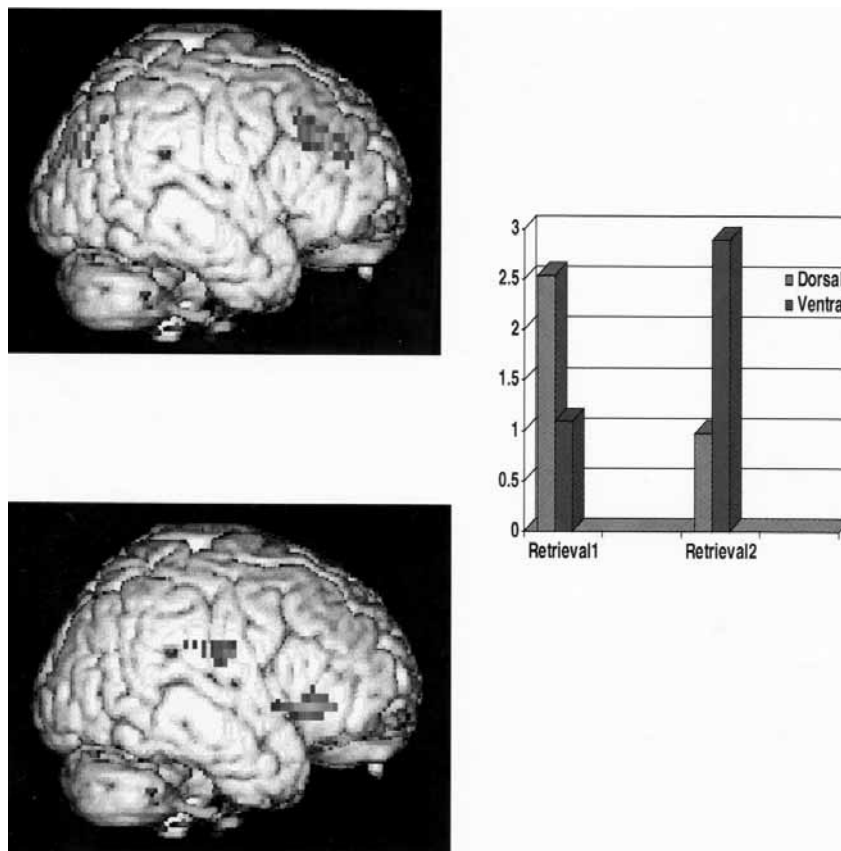SHALLICE: FRACTIONATION OF SUPERVISORY CONTROL   949

FIGURE 68.6 Activations of the right DLPFC and the right insula/VLPFC during the two critical conditions of the study reported by Fletcher, Shallice, Frith, and colleagues (1998), namely, organized list recall (retrieval 1) and paired associate recall (retrieval 2). Each was compared with its own control task, which involved only repetition. (See color plate 50.)

damaged in the patients with right frontal lesions studied by Stuss and colleagues (1994) comes into play when checking or monitoring operations are required. Such processes are much more necessary when retrieving a structured list than when retrieving single words. This is especially the case because the single words cannot be potentially confused with any other words being recalled, as they are known to be members of the specific category indicated by the cue words and the category is not repeated across the experiment.

Since then our group has completed a number of memory experiments involving contrasts between conditions in which different degrees of checking would be expected. In some cases, as in the study reported by Fletcher and colleagues, the right but not the left DLPFC was activated in the critical contrast where more checking was required. This occurred in a study of Henson, Rugg, and colleagues (1999) in which subjects had to rate for each word they remembered in a word recognition task whether they could clearly "recollect" the word being presented earlier or just "knew" it had occurred but had no specific memory. The latter condition is slower and would typically require a further check that fails. A similar result also occurred when the correct response had to be distinguished from competing similar

alternatives (Henson et al., 2002). In these cases, only the right DLPFC was activated in the critical contrast.

However, in other studies (e.g., Henson, Shallice, and Dolan, 1999: Henson et al., 2000) the left DLPFC was also significantly activated relative to a control baseline. Typical of these studies was the study of Henson, Shallice, and Dolan (1999), which used a so-called source memory paradigm derived from Jacoby (1996). Participants had to determine whether a previously presented item was in exactly the same setting as when it had occurred before. No responses had to be given to items that had occurred but in a slightly different setting; they were excluded. This condition was contrasted with one in which subjects had only to decide whether or not each item had occurred before—an inclusion decision. The former condition obviously requires more checking. The study used a blocked analysis procedure, standard in early functional imaging experiments. However, the results have been essentially replicated by Rugg, Henson, and Robb (2003), in a study that used an event-related design.

In the study by Henson and colleagues, both DLPFCs were activated in the exclusion retrieval condition. However, the right DLPFC region activated was much larger than the
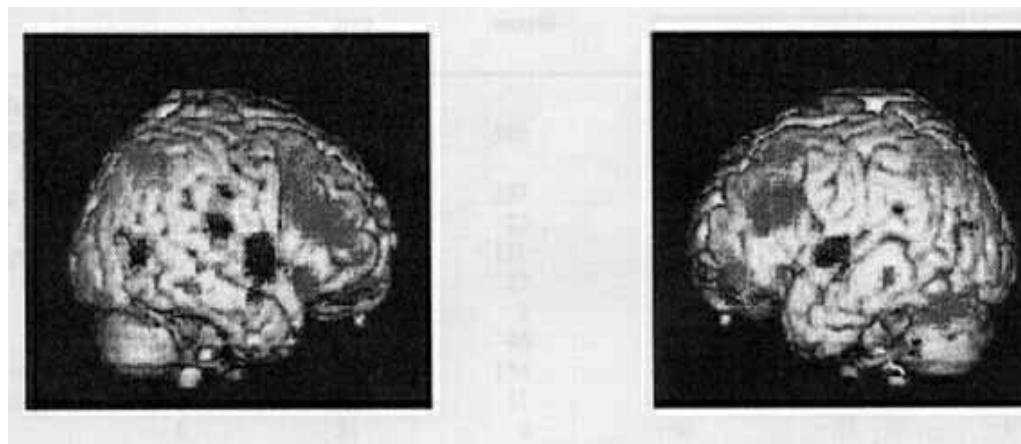
950   HIGHER COGNITIVE FUNCTIONS

FIGURE 68.7 Activations in the exclusion condition of the source memory study reported by Henson, Shallice, and Dolan (1999) (top) and of a left and right DLPFC voxel in each of the four con-ditions of the study. Abbreviations: E, encoding; X, exclusion retrieval; I, inclusion retrieval; C, control. (See color plate 51.)

left. Moreover, the pattern of activation across conditions for the two DLPFCs was subtly different (figure 68.7). The right DLPFC was much more activated by retrieval processes requiring checking (exclusion) than by encoding. A very different pattern was found in left DLPFC. Thus the balance between the top-down process required at encoding and the checking process required at retrieval is quite different between the two regions. Even when both dorsolateral regions are activated by processes requiring checking, the right region tends to be activated more.

In a memory experiment, alternative explanations are difficult to reject because we do not have a componential analysis of all the subprocesses involved. For instance, could activation of the right DLPFC merely indicate the degree of effort being made at retrieval? Early EEG studies by Wilding and Rugg (1996) showed that there is a right frontal wave at retrieval that occurs very late; it does not begin until at least 1400 ms after stimulus, which clearly favors a checking account.

More conclusive, however, is that right DLPFC effects occur in paradigms with no relation to memory. For example, Posner and Petersen (1990) argued that right

DLPFC was involved in vigilance operations. Another example, from the language domain, is provided by the study of Sharp, Scott, and Wise (2003). Participants in that study had to make semantic or syllabic decisions about words presented either normally or phonologically degraded. The use of phonologically degraded stimuli led to decreased accuracy, especially for the semantic task, which would lead to greater checking. Increased activation of right DLPFC regions occurred even though the stimuli were verbal.

NEUROPSYCHOLOGICAL EVIDENCE Easier to analyze than functional imaging experiments are neuropsychological ones. If a set of isolable subsystems is involved, then a full componential analysis of the tasks employed is less necessary than for functional imaging, particularly for the processes not affected by the lesion. Moreover, experimenters can be helped by the nature of the errors made. Thus, Reverberi and colleagues (2002) looked at what effects frontal lesions might have on acquisition of a rule. The patients saw a series of cards, each containing 10 circles in a 2×5 array. One circle was blue, and it moved from card to card in a predetermined fashion according to a rule that changed every five

to nine cards. Patients had to guess where on the next card the blue circle would be. Burgess and Shallice (1996) had already shown that patients with frontal lesions were impaired on this task. However to contrast rule attainment with a situation involving checking, an analogous set of cards, each with a red rather than blue circle, was introduced into each rule near the end of the sequence. The red circles moved according to a different rule. Subjects were told they only had to touch the red circle on each card, but as soon as the blue cards returned they were to resume obeying the "blue card rule."

Patients with left lateral lesions were very poor at acquiring the rule. By contrast, those with right lateral lesions were completely normal at acquiring the blue card rules. However, their rate of "capture errors" on returning to the blue cards was three times that of normal controls. They continued obeying the red card rule when the blue card rule should have been followed. They failed to check that the rule most activated implicitly was the correct one.

This section has reviewed in some detail studies identifying activation in DLPFC regions to show that as with parietal regions, there may be strong lateralization effects on functions, such as strategy production and checking/monitoring, that are not related to language per se. However, earlier it was argued that there are at least five different prefrontal regions with different cognitive functions involved in episodic memory paradigm. The next section therefore briefly considers the more anterior regions.

Anterior prefrontal systems

Classically, in single-cell recording studies, much more attention has been paid to dorsolateral and ventrolateral regions of prefrontal cortex than to the frontal polar regions. With functional imaging, however, activations have been increasingly recorded in the frontopolar region, or BA 10. In a recent meta-analysis, Christoff and Gabrieli (2000) found that during reasoning tasks frontopolar activation occurred at least as frequently as dorsolateral activation. However, activation of this area also occurred on a variety of other tasks, such as ones requiring subjects to create an order over a set of items, with each being selected just once, on certain working memory tasks, on tasks requiring information about the self, on episodic memory retrieval, and on a few others.

A general characteristic of these tasks is their complexity, and consequently it is very rare to have an adequate componential analysis of the task. When we lack a componential analysis of tasks, then neuropsychological findings, particularly strong dissociations, provide a much easier basis for initial analysis. However, few neuropsychological studies compare the effect of lesions of frontal polar regions with the effect of lesions of other areas of prefrontal cortex.

There is, however, an exception. Eslinger and Damasio (1985) described patient E.V.R. who had intact performance on cognitive tests of prefrontal function but was incapable of organizing himself over time in everyday life situations. E.V.R. became the starting point for Damasio's (1996) "somatic marker" theory, which he linked to the orbital prefrontal damage incurred by the patient. However, Shallice and Burgess (1991) produced an alternative account. They described three patients with frontal lobe damage who exhibited a similar dissociation between intact performance on standard cognitive tasks sensitive to frontal lobe damage and disordered performance on everyday life tasks. These three patients, however, all failed at one particular type of cognitive task: a task that involved the carrying out of multiple subtasks during which the patient had to follow a small set of simple rules. The subtasks had no relation to each other, and no cue was available as to when a participant had to switch from one subtask to another. The three patients tended to fixate on one of the tasks. It appeared that the need to carry out other tasks did not lead to interruption of ongoing behavior, as in normal subjects. Shallice and Burgess (1991) argued that their patients had lost the ability to set up or realize "intentional markers" that affect the need to alter behavior at some stage in the future according to one-off current requirements.

The best localized of the lesions in the three patients was bilateral and affected the frontopolar regions, BA 10 and 11 (figure 68.8). A later group study used a task working on similar principles with three unrelated subtasks. Patients with left anterior prefrontal lesions had no difficulty learning the task rules, remembering them, developing an appropriate strategy, or remembering what they had done when asked. However, such patients scored very poorly on the test as a whole. They did not switch sufficiently and broke task rules, both of which require setting up specifications for control of behavior at some time later. In an attempt to isolate the "intentional marker" component more formally in an imaging situation, Burgess, Quayle, and Frith (2001) asked subjects to carry out tasks of two types. One type was an "ongoing task," which subjects had to carry out for roughly 30 stimuli. In one condition this was the only type of task subjects had to perform. However, in two conditions subjects were instructed they had another task, an "intention" task, to carry out. In one condition, intention maintenance, the intention task was never realized. In another condition, intention realization, it became relevant about once every six stimuli.

The study utilized four different ongoing and intention tasks involving different lower-level cognitive domains (figure 68.9). The results were based on conjunction analyses over the four basic sets of tasks. Realization of an intention by comparison with its maintenance activated the right thalamus and right DLPFC, possibly suggesting successful moni-
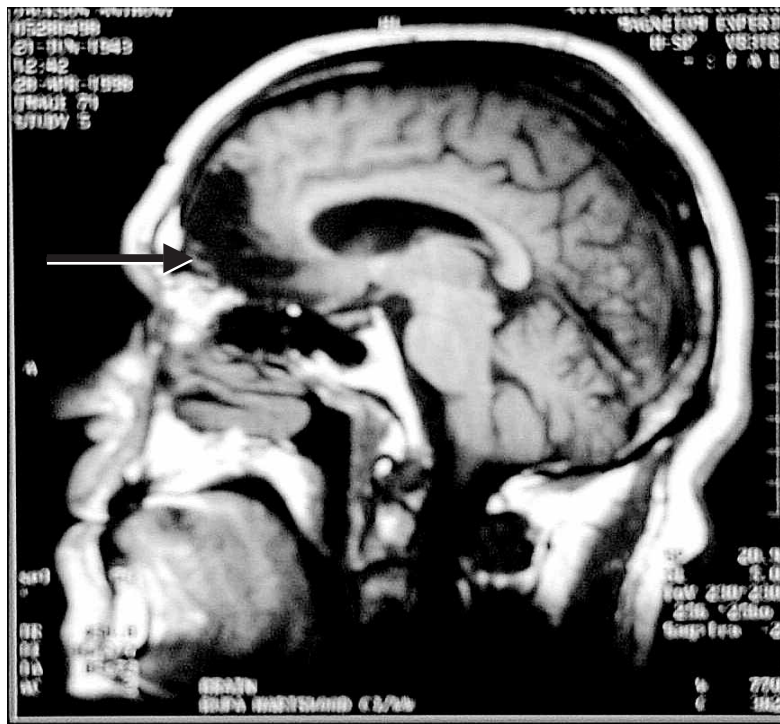
FIGURE 68.8   The lesion of patient A.P. of Shallice and Burgess (1991) with a severe impairment of "intention marker" realization. The lesion affects BA 10 and 11 bilaterally. (See color plate 52.)

toring. Maintenance of an intention by comparison with carrying out the ongoing task by itself also activated the right dorsolateral prefrontal region, but also, critically, the left and right frontal pole.

The region activated in this comparison, especially the left prefrontal region (−30, 62, −6), was in a virtually identical position to that found in another study of Koechlin and colleagues (1999; −36, 57, 9) and was similar to ones in related studies of Okuda and colleagues (1998) and Burgess, Scott, and Frith (2003). In the critical condition in the study reported by Koechlin and colleagues, subjects also had to do two tasks. Presented with a study of letters such as *A, B, L, t, e, a*, they had to decide whether successively presented letters were also in immediate succession in the word *tablet*. However, they, too, had a second task, which applied only when there was a change from uppercase to lowercase letters. Then subjects had to decide whether the letter was a *t*.

Koechin and colleagues called their critical condition "branching," emphasizing a need to return to a main task after carrying out a subroutine. Burgess and colleagues preferred the more general notion of anticipatory processing of McCarthy and Warrington (1990) and linked it to the old *Gestalt* views of Lewin and Zeigarnick regarding "goal tension," which would be the processing basis of holding and realizing an intention. In the model presented earlier (see figure 68.4), these views would correspond to the delayed intention realization process.

Conclusions

In the perspective presented in this chapter, control of nonroutine behavior involves a variety of different types of subsystem, each with abstract specifications. At the lowest supervisory level, Petrides's understanding of ventrolateral cortex as concerned with maintenance of ongoing operations can be developed. It has been suggested to hold the process of posing specific top-down requirements for particular lower-level systems such as language processing, short-term memory, or episodic memory (see, e.g., Henson, Shallice, and Dolan, 1999). Damage would lead to specific impairments, such as dynamic aphasia or rare forms of amnesia. These impairments have not been considered in this chapter.

At the next higher level would be dorsolateral structures. For these, the subject's task and immediate goals are well-defined and are the dominant motivational influences on cognition in the immediately preceding few-second period. What is required is a strategy to implement the task, and to check that the behavior that follows satisfies the task goals. It has been argued that in the human brain, the systems responsible for these processes are relatively lateralized to the left and right, respectively, at least for verbal and symbolic processing.

At the next higher level are situations where the cognitive mode needs to change or where the task and its goals, while abstractly active, have not been controlling behavior in the preceding few seconds. The goal structure currently con-
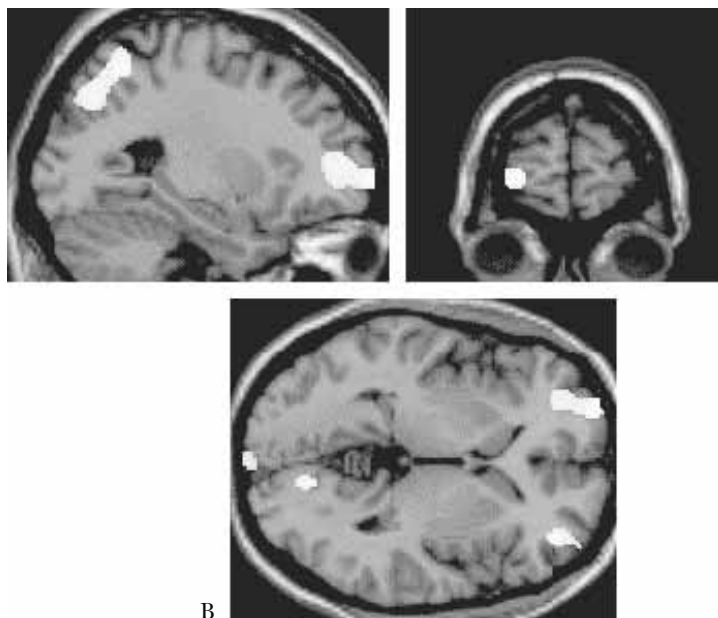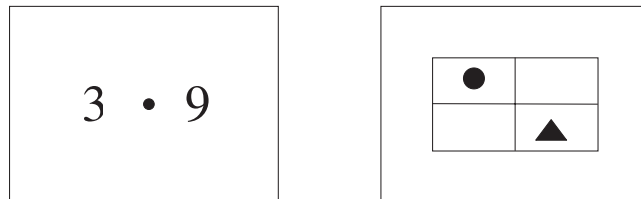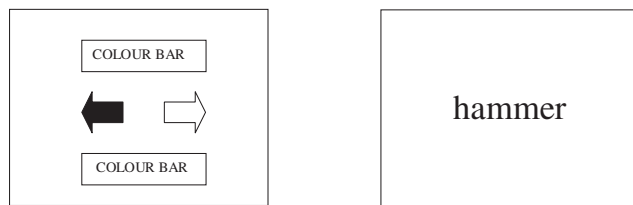
SHALLICE: FRACTIONATION OF SUPERVISORY CONTROL   953

FIGURE 68.9 (*A*) Stimuli used by Burgess, Quayle, and Frith (2001) in their study of maintenance and realization of intentions for convolution of the critical maintenance of intention condition compared with the ongoing task, across the four different types of ongoing task. (*B*) Activation sites. (See color plate 53.)

trolling immediate behavior needs to be interrupted, and a new set of goals, possibly prefigured by previously produced intentions, needs to be brought into play. This, it is suggested, is the role of the anterior prefrontal cortex. The different subprocesses, however, are not independent processes. Collectively they form a supervisory system for coping with nonroutine situations by top-down modulation of systems implementing the routine.

REFERENCES

BADDELEY, A. D., 1986. *Working Memory*. Oxford, England: Oxford University Press.

BRAVER, T. S., J. D. COHEN, and D. M. BARCH, 2002. The role of prefrontal cortex in normal and disordered cognitive control: A cognitive neuroscience perspective. In *Frontal Lobe Function*, D. Stuss and R. T. Knight, eds. Oxford, England: Oxford University Press, pp. 428–447.

BURGESS, P., A. QUAYLE, and C. D. FRITH, 2001. Brain regions involved in prospective memory as determined by positron emission tomography. *Neuropsychologia* 39:545–555.

BURGESS, P. W., S. K. SCOTT, and C. D. FRITH, 2003. The role of rostral frontal cortex (area 10) in prospective memory: A lateral versus medial dissociation. *Neuropsychologia* 41:906–916.

BURGESS, P., and T. SHALLICE, 1996. Bizarre responses, rule detection and frontal lobe lesions. *Cortex* 32:241–260.

BUTTER, C. M., 1964. Habituation to novel stimuli in monkeys with selective frontal lesions. *Science* 144:313–315.

CABEZA, R., and L. NYBERG, 2000. Imaging cognition. II. An empirical review of 275 PET and fMRI studies. *J. Cogn. Neurosci.* 12:1–47.

CHRISTOFF, K., and J. D. E. GABRIELI, 2000. The frontopolar cortex and human cognition: Evidence from a rostrocaudal hierarchical organisation within the human prefrontal cortex. *Psychobiology* 28:168–186.

COOPER, R., and T. SHALLICE, 1995. SOAR and the case for unified theories of cognition. *Cognition* 55:115–149.

COOPER, R., and T. SHALLICE, 2000. Contention scheduling and the control of routine activities. *Cogn. Neuropsychol.* 17:297–338.

DAMASIO, A. R., 1996. The somatic marker hypothesis and the possible functions of the prefrontal cortex. *Philos. Trans. R. Soc. Series B* 351:1413–1420.

DAMASIO, A. R., N. R. GRAFF-RADFORD, P. J. ESLINGER, H. DAMASIO, and R. KAWASHIMA, 1985. Amnesia following basal forebrain lesions. *Arch. Neurol.* 42:263–271.

DE RENZI, E., and P. NICHELLI, 1975. Verbal and non-verbal short-term memory impairment following hemispheric damage. *Cortex* 11:341–354.

DELLA MALVA, C. L., D. T. STUSS, J. D'ALTON, and J. WILLMER, 1993. Capture errors and sequencing after frontal brain lesions. *Neuropsychologia* 31:363–372.

D'ESPOSITO, M., G. K. AGUIRRE, E. ZARAHN, and D. BALLARD, 1998. Functional MRI studies of spatial and non-spatial working memory. *Cogn. Brain Res.* 7:1–13.

DUNCAN, J., 2001. An adaptive coding model of neural function in prefrontal cortex. *Nat. Rev. Neurosci.* 2:820–829.

DUNCAN, J., and E. K. MILLER, 2002. Cognitive focus through adaptive neural coding in the primate prefrontal cortex. In *Principles of Frontal Lobe Function*, J. Duncan and E. K. Miller, eds. New York: Oxford University Press, pp. 278–291.

954   HIGHER COGNITIVE FUNCTIONS

DUNCAN, J., and A. M. OWEN, 2000. Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends Neurosci.* 23:475–483.

DUNCAN, J., R. J. SEITZ, J. KOLODNY, D. BOR, H. HERZOG, A. AHMED, F. N. NEWELL, and H. EMSLIE, 2000. A neural basis for general intelligence. *Science* 289:457–460.

ESLINGER, P. J., and A. R. DAMASIO, 1985. Severe disturbance of higher cognition after bilateral frontal lobe ablation: Patient EVR. *Neurology* 35:1731–1741.

FLETCHER, P., and R. N. A. HENSON, 2001. Frontal lobes and human memory: Insights from functional imaging. *Brain* 124:849–881.

FLETCHER, P. C., T. SHALLICE, and R. J. DOLAN, 1998. The functional roles of prefrontal cortex in episodic memory. I. Encoding. *Brain* 121:1239–1248.

FLETCHER, P. C., T. SHALLICE, C. D. FRITH, R. S. J. FRACKOWIAK, and R. J. DOLAN, 1998. The functional roles of prefrontal cortex in episodic memory. II. Retrieval. *Brain* 121:1249–1256.

FOX, J., and S. K. DAS, 2000. *Safe and Sound: Artificial Intelligence in Hazardous Applications.* Menlo Park, Calif.: AAAI Press.

FRITH, C. D., 2000. The role of dorsolateral prefrontal cortex in the selection of action as revealed by functional imaging. In *Control of Cognitive Processes: Attention and Performance*, S. Monsell and J. Driver, eds. Cambridge, Mass.: MIT Press, pp. 549–565.

FUSTER, J. M., and G. E. ALEXANDER, 1971. Neuron activity related to short-term memory. *Science* 173:652–654.

GOLDMAN-RAKIC, P., 1987. Circuitry of primate prefrontal cortex and regulation of behaviour. In *Handbook of Physiology: The Nervous System*, F. Plum, ed. Bethesda, Md.: American Psychological Society, pp. 373–417.

GURNEY, K., T. J. PRESCOTT, and P. REDGRAVE, 2001. A computational model of action selection in the basal ganglia. I. A new functional anatomy. *Biol. Cybernet.* 84:401–410.

HENSON, R. N. A., M. D. RUGG, T. SHALLICE, and R. J. DOLAN, 2000. Confidence in word recognition: dissociating right prefrontal roles in episodic retrieval. *J. Cogn. Neurosci.* 12:913–923.

HENSON, R. N. A., M. D. RUGG, T. SHALLICE, O. JOSEPHS, and R. J. DOLAN, 1999. Recollection and familiarity in recognition memory: An event-related fMRI study. *J. Neurosci.* 19:3962–3972.

HENSON, R. N. A., T. SHALLICE, and R. J. DOLAN, 1999. The role of right prefrontal cortex in episodic retrieval: An fMRI test of the monitoring hypothesis. *Brain* 122:1367–1381.

HENSON, R. N. A., T. SHALLICE, O. JOSEPHS, and R. J. DOLAN, 2002. Functional magnetic resonance imaging of proactive interference during spoken recall. *NeuroImage* 17:543–558.

JACOBSEN, C. F., 1935. Functions of frontal association cortex in primates. *Arch. Neurol. Psychiatry* 33:558–560.

JACOBY, L. L., 1996. Associating automatic and consciously controlled effects of study-test compatibility. *J. Mem. Lang.* 35:32–52.

JAHANSHAHI, M., G. DIRNBERGER, R. FULLER, and C. D. FRITH, 2000. The role of the dorsolateral prefrontal cortex in random number generation: A study with positron emission tomography. *NeuroImage* 12:713–725.

JAHANSHAHI, M., P. PROFICE, R. G. BROWN, M. C. RIDDING, G. DIRNBERGER, and J. C. ROTHWELL, 1998. The effects of transcranial magnetic stimulation over the dorsolateral prefrontal cortex on suppression of habitual counting during random number generation. *Brain* 121:1533–1544.

JUEPTNER, M., K. M. STEPHAN, C. D. FRITH, D. J. BROOKS, R. S. J. FRACKOWIAK, and R. E. PASSINGHAM, 1997. Anatomy of motor learning. I. Frontal cortex and attention to action. *J. Neurophysiol.* 77:1313–1324.

KNIGHT, R. T., 1984. Decreased response to novel stimuli after prefrontal lesions in man. *Electroencephalogr. Clin. Neurophysiol.* 59:9–20.

KOECHLIN, E., G. BASSO, P. PIETRINI, S. PANZER, and J. GRAFMAN, 1999. The role of prefrontal cortex in cognition. *Nature* 399:148–151.

LEPAGE, M., O. GHAFFAR, E. NYBERG, and E. TULVING, 2000. Prefrontal cortex and episodic memory retrieval mode. *Proc. Natl. Acad. Sci. U.S.A.* 97:506–511.

MANDLER, G., 1967. Organizational memory. In *The Psychology of Learning and Motivation*, K. Spence and J. T. Spence eds. New York: Academic Press, pp. 327–372.

MCCARTHY, R. A., and E. K. WARRINGTON, 1990. *Cognitive Neuropsychology.* London: Academic Press.

MCDERMOTT, J., and C. FORGY, 1978. Production system conflict resolution strategies. In *Pattern-Directed Inference Systems*, D. A. Waterman and F. Hayes-Roth, eds. New York: Academic Press.

MOSCOVITCH, M., 1994. Cognitive resources and dual-task interference effects in normal people: The role of the frontal lobes and medial temporal cortex. *Neuropsychology* 8:524–533.

NEWELL, A., 1990. *Unified Theories of Cognition.* Cambridge, Mass.: Harvard University Press.

NORMAN, D. A., and T. SHALLICE, 1986. Attention to action: Willed and automatic control of behaviour. In *Consciousness and Self Regulation: Advances in Research*, vol. IV, R. J. Davidson, G. E. Schwartz, and D. Shapiro, eds. New York: Plenum Press, pp. 1–18.

OKUDA, J., T. FUJII, A. YAMADORI, R. KAWASHIMA, T. TSUKIURA, and R. FUKATSU, 1998. Participation of the prefrontal cortex in prospective memory: Evidence from a PET study in humans. *Neurosci. Lett.* 253:127–130.

OWEN, A. M., J. D. DOWNES, B. J. SAHAKIAN, C. E. POLKEY, and T. W. ROBBINS, 1990. Planning and spatial working memory following frontal lobe lesions in man. *Neuropsychologia* 28:1021–1034.

OWEN, A. M., N. J. HERROD, D. K. MENON, J. C. CLARK, S. P. DOWNEY, T. A. CARPENTER, P. S. MINHAS, F. E. TURKHEIMER, E. J. WILLIAMS, T. W. ROBBINS, B. J. SAHAKIAN, M. PETRIDES, and J. D. PICKARD, 1999. Redefining the functional organisation of spatial and non-spatial working memory processes within human lateral prefrontal cortex. *Eur. J. Neurosci.* 11:567–574.

PETRIDES, M., 1994. Frontal lobes and working memory: Evidence from investigations of the effects of cortical excisions in non-human primates. In *Handbook of Neuropsychology*, F. Boller and J. Grafman, eds. Amsterdam: Elsevier, pp. 59–84.

POSNER, M. I., and S. E. PETERSEN, 1990. The attention system of the human brain. *Annu. Rev. Neurosci.* 13:25–42.

RAICHLE, M. E., J. A. FIEZ, T. O. VIDEEN, A.-M. K. MACLEOD, J. V. PARDO, P. T. FOX, and S. E. PETERSEN, 1994. Practice related changes in human brain functional anatomy during nonmotor learning. *Cereb. Cortex* 4:8–26.

REVERBERI, C., A. LAVARONI, G. L. GIGLI, M. SKRAP, and T. SHALLICE, 2002. Inductive inferences and frontal cortex. *Cortex* 38:899–902.

ROWE, J., I. TONI, O. JOSEPHS, R. S. J. FRACKOWIAK, and R. E. PASSINGHAM, 2000. Separate fronto-parietal systems for selection versus maintenance in working memory. *Science* 288:1656–1660.

RUGG, M. D., R. N. A. HENSON, and W. G. K. ROBB, 2003. Neural correlates of retrieval processing in the prefrontal cortex during recognition and exclusion tasks. *Neuropsychologia* 41:40–52.

RYPMA, B., and M. D'ESPOSITO, 1999. The roles of prefrontal brain regions in components of working memory: Effects of memory load and individual differences. *Proc. Nati. Acad. Sci. U.S.A.* 96:6558–6563.

SHALLICE, T., 1982. Specific impairments of planning. *Philos. Trans. R. Soci. Lond. B* 298:199–209.

Shallice, T., and P. Burgess, 1991. Deficits in strategy application following frontal lobe damage in man. *Brain* 114:727–741.

Shallice, T., and P. W. Burgess, 1996. Domains of supervisory control and the temporal organisation of behaviour. *Philos. Trans. R. Soc. Lond. B* 351:1405–1412.

Shallice, T., and M. E. Evans, 1978. The involvement of the frontal lobes in cognitive estimation. *Cortex* 14:294–303.

Shallice, T., P. C. Fletcher, C. D. Frith, P. Grasby, R. S. J. Frackowiak, and R. J. Dolan, 1994. Brain regions associated with the acquisition and retrieval of verbal episodic memory. *Nature* 386:633–635.

Shallice, T., and G. Vallar, 1990. The impairment of auditory-verbal short-term storage. In *Neuropsychological Impairments of Short-Term Storage*, G. Vallar and T. Shallice eds. Cambridge, England: Cambridge University Press.

Sharp, D. J., S. K. Scott, and R. J. S. Wise, (in press). Monitoring and the controlled processing of meaning: Distinct prefrontal systems. *NeuroImage*.

Stuss, D., M. P. Alexander, C. Palumbo, L. Buckle, L. Sayer, and J. Pogue, 1994. Organisational strategies of patients with unilateral or bilateral frontal lobe injury in word list learning tasks. *Neuropsychology* 8:355–373.

Tulving, E., S. Kapur, and F. I. M. Craik, 1994. Hemispheric encoding/retrieval asymmetry in episodic memory: Positron emission tomography findings. *Proc. Natl. Acad. Sci. U.S.A.* 91: 2012–2015.

Verin, M., A. Partiot, B. Pillon, C. Malapani, Y. Agid, and B. Dubois, 1993. Delayed response tasks and prefrontal lesions in man: Evidence for self-generated patterns of behaviour with poor environmental modulation. *Neuropsychologia* 31:1379–1396.

Warrington, E. K., and T. Shallice, 1969. The selective impairment of auditory verbal short-term memory. *Brain* 92:885–896.

Wilding, E. L., and M. D. Rugg, 1996. An event-related potential study of recognition memory with and without retrieval of source. *Brain* 119:889–906.