

# Locating and Fractionating Working Memory Using Functional Neuroimaging: Storage, Maintenance, and Executive Functions

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**ABSTRACT** Working memory encompasses the short-term store of information and operations on that information. We review functional neuroimaging studies that have attempted to determine cortical areas involved in working memory functions. Current research suggests distinct systems for verbal information, visual objects, and spatial locations. Passive storage buffers appear to be located in posterior brain areas, whereas active maintenance of the information involves ventrolateral prefrontal areas. More complex, executive operations appear to recruit dorsolateral prefrontal cortex and anterior cingulate cortex. The possible involvement of reciprocal circuits including frontal cortex, basal ganglia, and thalamus is also discussed. *Microsc. Res. Tech.* 51:45–53, 2000. © 2000 Wiley-Liss, Inc.

## INTRODUCTION

Memory is not monolithic. A number of memory systems can be distinguished by the length of time they store information, the amount of information that can be stored, the form of the storage, and the cognitive functions that the storage serves (Jonides et al., 1996). They can also be distinguished by the cortical and subcortical systems that subservise them. Any list of the logically-necessary components of an information processing system—a *computational model* (Marr, 1982)—is likely to include a mechanism for the temporary storage of newly received information relevant to the currently ongoing processing. This concept of a temporary store has a long history in psychology. James identified the *specious present*—what appears to us consciously as the present—as constituting *primary memory*. He described it as having “a vaguely vanishing backward and forward extent,” but said that “its nucleus is probably the dozen seconds or so that have just elapsed” (p. 578). Broadbent (1958) and Sperling (1960) described perceptual stores that outlasted the processing of the stimulus. Atkinson and Shiffrin (1968, 1971) incorporated these notions into their canonical model of memory as a short-term store. Reflecting a zeitgeist of concern primarily for memory for verbal materials, their concept of the short-term store emphasized phonological and linguistic coding of material held for a short period before it was consolidated into long-term memory.

Baddeley (1986, 1992; Baddeley and Hitch, 1974) broadened the concept of a short-term store into what we now call *working memory*. In this formulation, working memory encompassed not only the storage of information but also the processing operations that make use of this information. There are differences among the many current conceptions of working memory, but they share certain common characteristics: Working memory is a system that (1) stores information briefly, (2) stores not only perceptual information

but also information derived from operations on the contents of the memory store, (3) can handle only a limited amount of information, (4) is rapidly accessible, (5) is subject to frequent updating and revision, and (6) is used in the service of higher cognitive processes (Jonides et al., 1996).

We shall review the accumulating evidence that there are several dissociable working memory systems. Baddeley (1986, 1992) described two storage systems—one for linguistic information and one for visuospatial information—that operated in the service of a central executive. We shall briefly review behavioral and neuropsychological findings but we shall concentrate on the recent and important neuroimaging studies—primarily using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI)—that have distinguished working memory storage systems for verbal information, visual objects, and spatial locations. Neuroimaging studies have distinguished components of the working memory systems that serve as storage buffers from those concerned with maintenance of the information and, in turn, from executive processes concerned with carrying out operations on the stored information. The executive processes, too, have been elaborated and are now being explored.

## DISSOCIATING WORKING MEMORIES BY MODALITY

The primary paradigm for distinguishing working memories has been the *double dissociation*. In behavioral work with normal individuals, this involves demonstrating that a variable, A, affects one type of working memory but not a second type, whereas a second variable, B, affects the second type of working memory but not the first. In neuropsychological studies, a dou-

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ble dissociation is demonstrated when one type of working memory is intact in a brain-damaged individual whereas a second type is impaired, but in another individual, the first type is impaired and second type is intact. In neuroimaging studies, a double dissociation is demonstrated when one set of brain areas is activated when one type of working memory is challenged whereas a different set of brain areas is activated when another type of working memory is challenged.

### Behavioral and Neuropsychological Dissociations

One example of a behavioral double dissociation employed selective interference. den Heyer and Barrett (1971) presented individuals with eight letters randomly positioned in a  $4 \times 6$  matrix. The matrix was removed and followed by a 10-second retention interval. There were three different conditions, defined by the task during the retention interval: (1) to do nothing, (2) to judge which two of three matrices containing three dots were the same (which should selectively interfere with memory for the spatial arrangement of the letters), or (3) mentally to add five aurally-presented numbers (which should selectively interfere with memory for the identity of the letters). Recall of the identity of the letters was 56% worse with the dot comparison task but 68% worse with mental arithmetic; recall of the location of the stimuli was 45% worse with mental arithmetic, but 90% worse with dot comparisons. The differential interference was taken as evidence for the dissociability of working memory for location and for verbal identity.

A pair of reported case studies exemplifies a neuropsychological double dissociation. Patient P.V. had an extensive left hemisphere lesion due to a stroke 5 years before testing (Basso et al., 1982). Her ability to recall aurally-presented digits (digit span) was badly impaired (she could only recall one string of five digits out of 10 strings presented) but her span for recalling successive locations (the Corsi Blocks test) was slightly better than normal. Another patient, E.L.D., had an aneurysm in the middle cerebral artery leading to hematoma in the Sylvian fissure (Hanley et al., 1991). She recalled each of three sequences of six letters correctly, whereas controls recalled only 1.4 sequences correctly on average. On the Corsi Blocks test, she could not recall five locations correctly, whereas 70% of normals did so. The pair of patients defines a double dissociation between memory for spatial location and verbal identity.

### Dissociations Using Neuroimaging

The clearest evidence for dissociations among working memory systems comes from neuroimaging studies. In the studies that will be described in some detail, exactly the same stimuli are presented with two different memory instructions. In one condition, the individual is to remember one aspect of the stimulus, such as its verbal identity; in the other condition, the individual is to remember a different aspect, such as its location. If the same stimuli generate different patterns of cortical activation under different memory instructions, that is strong evidence for distinct memory systems.

**Dissociation of Verbal and Spatial Working Memory.** Smith et al. (1996) dissociated verbal and spatial working memory using PET. They used a running memory task in which the individual had to determine whether each stimulus matched or did not match the stimulus that had appeared three items previously in the sequence (called the three-back task). Upper- and lower-case letters were displayed one at a time on the circumference of an imaginary circle. In one condition, the match/mismatch judgment was made on the identity of the letter, without regard to spatial location. In the other condition, the judgment was made on the spatial location of the letter in the display, without regard to the identity of the letter. Compared to control conditions, the verbal identity task produced activations in left posterior parietal cortex, in Broca's area, and in dorsolateral prefrontal cortex (DLPFC) in the left hemisphere. By contrast, spatial instructions produced activations in posterior parietal areas and in DLPFC, but in the right hemisphere. Activation was also found in right hemisphere premotor areas. The clear lateralization of the sites of activation in the two memory conditions is strong evidence that the working memory systems for verbal identity and spatial location are distinct.

**Dissociation of Spatial and Object Working Memory.** Smith et al. (1995) recorded PET activations in a delayed match-to-sample task with nonsense shapes. In one condition, the task was to determine whether a probe item matched the identity of one of the three objects just presented. The objects were randomly-generated shapes and thus not easily named. In the other condition, the task was to determine whether the probe item appeared in the same location as any of the items in the memory set. With spatial memory instructions, activations were found bilaterally in posterior parietal cortex, frontally in the right-hemisphere DLPFC and ventrolateral prefrontal cortex (VLPFC, Brodmann's Area, BA, 47), and in the anterior cingulate cortex (ACC). With object memory instructions, the only significant activations were in the left hemisphere, the posterior parietal cortex, and the inferotemporal cortex. McCarthy et al. (1996) specifically examined activation of regions of interest (ROI) in prefrontal cortex with fMRI using more complex spatial and object working memory tasks than had Smith et al. (1995). They used a running memory task with sequences of 18 or 19 squares or nonsense shapes. The task was to say whether the current stimulus matched the identity (for object memory) or location (for spatial memory) of any prior stimulus. McCarthy et al. (1996) examined ROIs in PFC and found significant activation in middle frontal gyrus (MFG) but not superior frontal gyrus (SFG) or inferior frontal gyrus (IFG). In right hemisphere, they found equal activation of MFG for object identity and location; in left hemisphere, they found greater activation for object identity than for location. It appears, then, that memory for visual objects results in greater left hemisphere activation than does memory for spatial location. Results such as these show that Baddeley's (1986, 1992) storage buffer for visuospatial information, the visuospatial sketchpad, can be further subdivided into two functionally and anatomically distinct systems for visual object working memory and another for visual spatial working memory.

**Meta-Analytic Evidence.** Because of the variation in tasks that have been used to study working memory and because of the relatively low resolution of current neuro-

TABLE 1. Brain areas (Brodmann's areas) showing activation in simple maintenance tasks: proportion of experiments with activation in left, right, or both hemispheres<sup>1</sup>

Modality	DLPFC (9/46)	VLPFC (44/45/47)	SMA (6)	PM (6)	Parietal (40/19/7)
Spatial					
Expts. with activation	3/10	7/10	4/9	9/10	10/10
Left hemisphere	.00	.00	.25	.00	.10
Right hemisphere	.33	.86	.25	.22	.20
Bilateral	.67	.14	.50	.88	.70
Nonspatial					
Expts. with activation	3/12	9/12	5/12	3/12	8/12
Left hemisphere	.00	.67	.60	.33	.75
Right hemisphere	.33	.00	.20	.00	.00
Bilateral	.67	.33	.20	.67	.25

<sup>1</sup>Adapted from D'Esposito et al. (1998).

imaging techniques, areas of activation from any one study must be interpreted with caution. Because a number of such studies have now been reported, it has been possible to carry out meta-analyses, examining trends across studies. D'Esposito et al. (1998) surveyed experiments reporting imaging of maintenance of information in working memory, 10 in spatial working memory (Anderson et al., 1994; Baker et al., 1996; Courtney et al., 1996; Jonides et al., 1993; Owen et al., 1996; Smith et al., 1995, 1996; Sweeney et al., 1996) and 12 in nonspatial (verbal or object) working memory (Baker et al., 1996; Becker et al., 1996; Courtney et al., 1996; Fiez et al., 1996; Grasby et al., 1993; Haxby et al., 1995; Paulesu et al., 1993; Salmon et al., 1996; Smith et al., 1995, 1996). Table 1 shows, for each cortical region, for experiments that reported significant activation in that area, the proportion reporting left hemisphere, right hemisphere, and bilateral activation. The most salient features of these results are that these maintenance tasks activate ventral PFC much more than they do dorsal PFC, and, moreover, that the activation tends to be more on the right for spatial working memory tasks and more on the left for nonspatial working memory tasks. In addition, spatial working memory tasks tend to elicit bilateral parietal activity, whereas nonspatial tasks tend to elicit left-lateralized activity. Premotor activity is more common in spatial tasks and it tends to be bilateral or right hemisphere. Nevertheless, three recent studies cast doubt on the conclusion that object and spatial working memories activate different portions of frontal cortex. Postle and D'Esposito (1999) used a delayed-recognition test in which both object position and identity were probed on each trial, with the order in which they were encoded and tested varying from trial to trial. Both tasks produced retention-period activation in ventral PFC (BA 44/45/47) and in dorsal PFC (BA 9/46). The activation was bilateral in most subjects. It did not differ as a function of the type of memory being tested. Postle et al. (2000) administered two-back and three-back tests of spatial location and object identity. Three experiments failed to find any dissociation of prefrontal cortical activity associated with spatial working memory and working memory for object identity. Nystrom et al. (2000) found no differences in prefrontal activation in comparisons of name identity (letters), object identity (abstract shapes), or spatial locations. It is not clear how to reconcile the findings of studies reporting differences in the activation patterns associated with spa-

tial and nonspatial working memory with the recent studies that were unable to find differences. It may be that there are, indeed, differences but they are only seen with certain tasks and at certain load levels. An alternative explanation is that there are no differences and that the differences observed in the earlier studies were due to the use of different stimuli to test the different types of memory (Postle et al., 2000).

### DISSOCIATING STORAGE AND MAINTENANCE

A readily-available strategy for maintaining verbal information in working memory is subvocal rehearsal. Subvocal rehearsal is likely to involve ventral frontal cortex, particularly Broca's area. Awh et al. (1996) proposed that active maintenance of information in verbal working memory tasks occurs in VLPFC in the left hemisphere, whereas passive storage occurs in left parietal areas. Neuropsychological evidence does show that parietal damage in the left hemisphere produces impairments in verbal short-term memory whereas damage in the right hemisphere produces impaired visuospatial short-term memory (McCarthy and Warrington, 1990). Awh et al. (1996) used a two-back running memory task in a PET study. They added a rehearsal control condition in which the person had to repeat the letter silently until the next one occurred. Subtracting the rehearsal control condition from the standard condition removed activation in Broca's area and left premotor cortex, although some supplementary motor area (SMA) activation remained. These results are consistent with a maintenance rehearsal mechanism for verbal working memory located in VLPFC.

Awh and Jonides (1998) and Smith and Jonides (1999) have proposed that movements of covert visual attention to to-be-remembered locations may serve the same maintenance function for spatial working memory as rehearsal does for verbal working memory. They speculate that the storage buffer for spatial information may be in right parietal areas and that frontal premotor areas may maintain the information through controlled movement of attention that serves as a spatial analog of subvocal rehearsal. In behavioral experiments, Awh et al. (1998) found that processing efficiency was increased at locations currently being held in spatial working memory. A sequence of letters was presented, followed by a 5,000-ms retention interval and then a probe letter. The primary task was to determine whether the letter appeared in the same location as one of the memory set letters. During the retention interval, a secondary shape identification task was presented. Responses to the shapes were significantly faster when they appeared in the same location as an item in the memory set as when they appeared in a different location. Conversely, performance was impaired when individuals were hindered during the retention interval in their ability to attend to the locations held in working memory. In this experiment, the primary task was to remember the location of a dot. During the retention interval, the subject had to make a color discrimination. The color stimulus was either a small patch in a location different from the to-be-recalled dot, presumably requiring a shift of spatial attention, or a large patch covering the entire area in

which stimuli could appear, presumably requiring no activation of focal attention. Performance on the primary spatial memory task was significantly worse with the small color stimulus than the large color stimulus. In a subsequent PET study, Awh et al. (1999) found that visual activity in extrastriate and parietal areas was enhanced when locations in the contralateral visual hemifield were held in working memory. Sets of nonsense characters were presented in the left or right visual hemifield and their locations were to be remembered. During the 6,000-ms retention interval, a reversing annular checkerboard was displayed. Activation in ROIs in visual areas (BA 17, 18, 19) were compared for memory retention and no-memory control conditions. Activation in the hemisphere contralateral to the field in which the to-be-remembered stimuli were presented was significantly higher than in the ipsilateral hemisphere. These results are consistent with the assertion that posterior cortical areas serve as a storage buffer for spatial location.

It is important to note that maintenance mechanisms such as subvocal rehearsal or covert movement of attention are voluntary, tactical devices that an individual may or may not employ. Not everyone rehearses to-be-remembered information subvocally. Among those who do, not everyone uses the same rehearsal strategy. One person might try to retain and rehearse as large a set as possible; another might rehearse the last several items; yet another may repeatedly rehearse only the last item. If visual attention is used as a rehearsal device for spatial information, it is likely that there is even more inter- and intra-individual variability than there is in subvocal rehearsal. Rehearsal—whether verbal or spatial—is a mechanism that can be, but need not be, recruited in service of retaining temporarily stored information in working memory.

#### TASKS THAT REQUIRE MORE THAN SIMPLE MAINTENANCE

Some working memory tasks seem inherently more complex and difficult than others. For example, a two-back running memory task seems subjectively much more demanding than a one-back or delayed match-to-sample task. More complex tasks are widely described as requiring *executive processes* that go beyond simple storage and maintenance. Even before attempting a formal definition of executive processes, it is possible to review extant studies for evidence of cortical activations that are unique to more complex tasks. In the meta-analysis already mentioned, D'Esposito et al. (1998) also examined more complex tasks, which they called maintenance-plus tasks. Six experimental conditions involved spatial working memory (McCarthy et al., 1994, 1996; Owen et al., 1996; Smith et al., 1996) and 12 involved nonspatial (verbal or object) working memory (Awh et al., 1996; Cohen et al., 1994; McCarthy, et al., 1996; Petrides et al., 1993a, 1993b; Salmon et al., 1996; Shumacher et al., 1996; Smith et al., 1996; Zatorre et al., 1994). Comparison of maintenance-plus tasks, summarized in Table 2, with simple maintenance tasks, shown in Table 1, shows a striking difference. Sixteen out of the 18 experimental conditions involving maintenance-plus resulted in DLPFC activation whereas only 6 of the 22 requiring only

TABLE 2. Brain areas (Brodmann's areas) showing activation in tasks requiring more than simple maintenance: proportion of experiments with activation in left, right, or both hemispheres<sup>1</sup>

Modality	DLPFC (9/46)	VLPFC (44/45/47)	SMA (6)	PM (6)	Parietal (40/19/7)
Spatial					
Expts. with activation	6/6	2/6	1/4	4/4	4/4
Left hemisphere	.00	.50	1.00	.00	.00
Right hemisphere	.50	.00	.00	.25	.00
Bilateral	.50	.50	.00	.75	1.00
Nonspatial					
Expts. with activation	10/12	6/12	2/10	8/10	10/10
Left hemisphere	.20	.67	1.00	.12	.00
Right hemisphere	.00	.00	.00	.12	.00
Bilateral	.80	.33	.00	.75	1.00

<sup>1</sup>Adapted from D'Esposito et al. (1998).

maintenance did so. The DLPFC activation tended to be bilateral, although there was some tendency for greater activation in the right hemisphere in complex spatial working memory tasks. Owen (1997) and Smith and Jonides (1999) have also surveyed published studies and have concluded similarly that tasks requiring only maintenance activate ventral areas of prefrontal cortex whereas more complex tasks requiring more executive management of processing activate more dorsal areas of prefrontal cortex. There is also some evidence that anterior portions of cingulate cortex may be involved (LaBerge, 1999; Smith and Jonides, 1999). It is also possible, of course, that cortical sites of executive processing are more diffuse but that they are coordinated or channeled through DLPFC and ACC. If this were the case, the actual sites might not be large or active enough to be visualized with current neuroimaging techniques and only the coordinating areas would show significant activation. In either event, damage to DLPFC would be expected to impair executive function.

#### Is DLPFC Recruited for More Complex Tasks?

The speculation is that more complex tasks recruit new cortical areas to manage executive processes, areas that are not activated in simpler, maintenance tasks. There are two lines of evidence that address this speculation. One comes from studies of memory-compromised populations, elderly adults and individuals with Alzheimer's Disease (AD). The other line of evidence comes from studies that systematically increase the memory demands within the same task, called the *method of parametric variation* (Smith and Jonides, 1997).

**Memory-Compromised Populations.** Relative to young adults, elderly adults show impairments in working memory in all modalities (e.g., Jenkins et al., 1999). Rutter-Lorenz et al. (2000) used PET with delayed match-to-sample tasks to look for age differences in the frontal lateralization of verbal and spatial working memory. They found lateralized posterior activations in both younger and older adults—left hemisphere for verbal memory, right hemisphere for spatial location. In the younger adults, activity in prefrontal ROIs was also lateralized by memory modality. Frontal activity in the older adults was bilateral in both tasks (and tended to be greater on the

side opposite the expected, left for spatial memory and right for verbal memory). They argued that the older adults had to recruit additional, bilateral, executive processing resources in order to maintain performance. Consistent with this interpretation, Reuter-Lorenz et al. (1999) showed in a behavioral study that bilateral presentation of letters in a match-to-sample task improved performance in older adults, but not in younger adults. In a PET study of individuals with mild AD, Becker et al. (1996) found that a high memory load (8 words to be recalled) compared to a lower memory load (3 letters or 1 letter) produced significant bilateral increases in PET activation in DLPFC in the AD patients, relative to normal controls matched for age. They argued that a compensatory reallocation of brain resources was taking place to support working memory, similar to the cortical recruitment proposed by Reuter-Lorenz et al. (2000). Herbster et al. (1996) reanalyzed the data collected by Becker et al. (1996) using principal components analysis (which shows areas in which activation covaries). They concluded that "at least in the early course of the dementia, the functional CNS organization of verbal memory systems remains normal" (p. 67). This suggests that, had the task been made sufficiently difficult, normal controls would have shown same activation. This, in turn, leads to a refinement of the original interpretation. It is not that memory-compromised individuals recruit new cortical resources for a task that is demanding for them, but rather they recruit resources that are available to intact individuals but not heavily used because the task does not seem so demanding. This conclusion must remain speculative because the evidence is limited and because Rypma et al. (2000) recently reported *reduced* DLPFC activation in older adults when memory demands were increased. An alternative view must also be considered. Hasher and Zacks (1988) proposed that the ability to inhibit the entry of extraneous or irrelevant material into working memory is compromised in old age. The age-related changes might be attributed to failures of inhibition rather than to compensatory recruitment. To generalize this to younger, uncompromised adults requires the implausible assumption that they undergo failure of processing inhibition under conditions of high load or demand.

**Method of Parametric Variation.** A straightforward way to examine the effects of greater memory load is to increase systematically the memory demands without changing the task itself. In one such study, Jonides et al. (1997) examined changes in PET activations in a running memory task as the load increased systematically from zero-back to three-back. (The zero-back task is one in which the individual compares each successive letter to a single letter held in memory throughout the sequence. Although an item must be held in working memory, no updating is required.) They identified ROIs from the three-back task, then traced activations in those regions across the lower load conditions. As the load increased, they found monotonic increases in activation in prefrontal cortex, bilaterally in BA 46 and 10 and in BA 9 in the right hemisphere. There were also increasing activations in Broca's Area and in supplementary and premotor areas (BA 6) bilaterally. Braver et al. (1997) carried out a very similar study using fMRI. They reported monotonic increases in activation in DLPFC (BA 9, 46) and VLPFC (BA 44) bilaterally. They also found increasing activation in left premotor, parietal bilaterally, and the right caudate

nucleus. Cohen et al. (1997) increased the analytic power of the method of parametric variation still further by using a long inter-item interval (10 seconds) and looking at changes in activation in ROIs over that interval. Posterior parietal activation increased linearly with load as did activation in Broca's Area. Activity in both of these areas diminished at the end of the interval (and did so sooner for lower memory load). DLPFC, however, showed a very large jump in activation from zero- and one-back to two- and three-back. Moreover, the activation remained constant throughout the 10-second delay interval. McIntosh et al. (1996) tested covariance structural equation models for PET activations in a working memory for faces task with short, intermediate, or long retention intervals (ranging from 1 to 21 seconds). The models were based on established neuroanatomical connections. Compared to perceptual control conditions, memory conditions resulted in interactions among hippocampal regions, cingulate gyrus (BA 23, 24), and inferior prefrontal regions (BA 47). Long delays elicited interactions with DLPFC (BA 46) bilaterally, consistent with the activation reported by Cohen et al. (1997) at high loads.

**Explanations for Increased Prefrontal Activation.** Three potential explanations have been alluded to for the bilateral increase in prefrontal activation in tasks that put high demands on working memory: (1) an active, compensatory, strategic (if non-conscious) recruitment of additional cortical processing resources; (2) a passive, reactive (and essentially epiphenomenal) increase in activation; and (3) a side effect of failures to inhibit extraneous processing. The failure-of-inhibition hypothesis may explain results with memory-compromised populations but seems unlikely to be a general explanation. The quantum jump in DLPFC activation found by Cohen et al. (1997) as the task went from one-back to two-back running memory tips the balance strongly in favor of the compensatory recruitment hypothesis and against the epiphenomenal activation hypothesis. A computational analysis of the one-back task might run as follows: The new item is compared to the item in memory and a response is given; the memory item is discarded and replaced by the new item, which can then be maintained by repeated subvocal rehearsal until the next item appears. (Alternatively, the response can be based simply on a feeling of familiarity or recency and no active effort made to retain the item in memory.) A computational analysis of the two-back task is rather different: The new item is compared to the oldest item in the memory set and a response is given; the oldest item in the memory set is then identified and discarded; the youngest item is recoded as the oldest and the new item is entered as the youngest; the set of two letters can then be rehearsed subvocally until the next item appears. Notice that executive control must be maintained at all times. The soon-to-be oldest item must be maintained in memory even as the former oldest item is called up and compared to the current item. In the one-back task, there is a period on each trial when the memory set is empty. Moreover, in the one-back task, the new item can simply be inserted in memory. In the two-back task, the new item must be tagged appropriately as the most recent item. The jump in activation levels from one- to two-back is consistent with this computational analysis that shows additional, new executive processes must be carried out.

## EXECUTIVE FUNCTIONS

Baddeley's (1986, 1992) model of working memory went beyond simple storage to include a central executive concerned with control processes. There are two questions to ask about the central executive. First, can the central executive be localized? As working memory tasks become more challenging, DLPFC becomes more active. The activation appears to be bilateral and independent of the modality in which the information is held. Could DLPFC, then, be the locus of the central executive? Second, can the central executive be fractionated? Can we identify component executive operations that can be distinguished either behaviorally or anatomically?

Smith and Jonides (1999) enumerated several executive processes: attention and inhibition, task management, planning, monitoring, and coding. We propose a refined and elaborated list of executive processes. From the most general to the most specific, the executive functions must include the following: (1) maintaining the task goals and constraints on achieving those goals; (2) planning and maintaining a sequence of subtasks; (3) scheduling processing, switching between subtasks (or tasks) as necessary; (4) updating and checking the contents of memory to determine the next step; and (5) focussing attention on relevant information and inhibiting attention to irrelevant information.

It is important to note that frontal brain damage impairs all of these executive functions. For example, Cummings (1993) summarizes evidence for *dorsolateral prefrontal syndrome*, which is characterized by neuropsychological sequelae to damage including decreased verbal and design fluency, abnormal motor programming, impaired set shifting, reduced learning and memory retrieval, and poor problem solving. Owen et al. (1990) also reported deficits in higher level planning in individuals with PFC damage.

In discussing executive functions, we will proceed from the most narrow and basic—focussing and inhibiting attention—to the broadest and most general—maintaining goals and constraints.

### Focussing and Inhibiting Attention

Focussing and maintaining attention is carried out by the parietal storage buffers and ventral frontal rehearsal systems. It has been suggested that inhibition—preventing inappropriate contents from entry into working memory—may be a higher-order, executive process (Jonides et al., 1998). Jonides et al. (1998) used PET with a delayed match-to-sample task in which a probe matched or did not match one of four to-be-remembered letters. They compared a condition in which the negative probe (mismatch) had previously been a target—presumably producing a bias toward a match response—with another condition in which there was no prepotent response. Comparison of the two conditions showed only one difference, greater activation in left VLPFC (BA 45) when the probe had previously been a target. D'Esposito et al. (1999) replicated the earlier study with event-related fMRI. They again found differential activation in left VLPFC, but only during the period in which the probe was presented. There were no differences during target presentation or memory retention period. By contrast, ex-

amination of a ROI in left DLPFC (BA 9, 46) showed no differential activation. They concluded that inhibiting attention to items competing for entry into working memory—interference resolution—is localized to ventral, inferior PFC. It is interesting that elderly adults, who have been presumed to have impaired inhibitory processes (Hasher and Zacks, 1988), fail to show this activation in left VLPFC (Jonides et al., 2000). Anatomically VLPFC was associated with simple maintenance rather than executive processes. Nevertheless, it is clear that item inhibition can be conceptualized as an executive operation just as item rehearsal was.

### Updating and Checking

We noted above that two- and three-back running memory tasks are particularly good examples of tasks requiring checking and updating. As described, Cohen et al. (1997) found higher DLPFC activation in two- and three-back than in zero- and one-back and found that it was maintained throughout the interval. Another example is the self-ordered pointing (SOP) task (Petrides et al., 1993a, 1993b). In this task the individual repeatedly sees a set of 8 to 12 items—words, objects, or nonsense drawings—and must point to a unique one on each trial (the items are rearranged randomly from trial to trial). In the SOP task, the memory set must be increased by one each time and each candidate for a response must be checked against the entire memory set. Both studies reported bilateral activation of DLPFC (BA 9, 46), consistent with the involvement of this area in updating and checking processes. Postle et al. (1999) compared conditions that required rearrangement of letters held in memory with other conditions in which the letters simply had to be maintained in the order presented. Probes queried whether a particular item was in a specified position either when the letters had been alphabetized or when they were in the order presented. Alphabetization produced differential activation in DLPFC, leading Postle et al. (1999) to conclude that executive control processes that can contribute to working memory function (but whose application is not unique to working memory) are mediated by prefrontal cortex.

### Maintaining a Sequence of Subtasks, Scheduling Processing, and Switching Between Tasks

The clearest evidence for cortical activations related to managing the sequence of processing comes from dual-task studies that require the concurrent performance of two tasks. D'Esposito et al. (1995) gave subjects two overlapping tasks: a semantic judgment task (determine whether each word in a sequence is an exemplar of the category, vegetable) and a spatial judgment task (determine which of two stimuli is a spatially-rotated version of a third stimulus). Functional MRI was used to compare activations in the dual-task condition with activations for the each of the tasks performed alone. D'Esposito et al. (1995) found differential activation in DLPFC (BA 9, 46) and in ACC. Corbetta et al. (1991) also found ACC activation in a divided attention task using PET. Successive displays could differ in shape, color, or speed of movement of the elements. Single-task blocks differed in only one aspect, such as color. They found that when the type of discrimination

to be made was known in advance, extrastriate areas were activated, but when the individual could not anticipate whether the discrimination would be on shape, color, or speed, activation was in ACC. ACC activation has also been observed in the Stroop color-word task (Pardo et al., 1990). The task is to name the color in which a word is presented. The ACC was selectively activated in the condition in which the word names a color different from the color in which it is displayed. Gehring et al. (1993), using event-related potential recordings, localized EEG activation following incorrect responses to the ACC. Carter et al. (1998) confirmed this localization using fMRI.

Processing two tasks at the same time requires simultaneous management of two streams of operations. Processing following errors may involve comparison of the just-performed erroneous response with the correct response or it may reflect competing response tendencies. Processing incongruent colors (which must be responded to) and words (which must not be responded to) clearly involves managing competing responses. LaBerge (1999) has argued that during these rapid considerations or comparisons, the component task operations must be held in working memory and executive commands must direct attention successively to (or away from) single components of the tasks. The attentional control is generated from information held in working memory storage of a processing or an action plan. We can speculate then that executive processes for directing attention to single tasks or for shifting attention between tasks are localized in DLPFC, whereas executive processes for dealing with multiple actions are found in ACC.

The story may, however, go deeper. Pashler et al. (1994) examined dual task performance in patients who had the corpus callosum severed, disconnecting the left and right cerebral cortex. The two tasks were presented such that each was directed to a different hemisphere. Dual task interference in these commissurotomy patients was the same as normal controls. This should not have been the case if a different executive process were managing each task. The finding suggests a role for subcortical structures such as the basal ganglia or thalamus. Cummings (1993) and Alexander and DeLong (1986) describe neural circuits that link areas of the frontal cortex with subcortical structures including basal ganglia and thalamus. Normally, basal ganglia are thought of as maintaining a coherent stream of motor behavior by blocking extraneous responses. There is such a circuit, projecting from SMA to basal ganglia to thalamus, which then projects back to SMA. In parallel with this motor circuit, however, is another projecting from DLPFC (as well as premotor and posterior parietal areas) to dorsolateral caudate to lateral dorsomedial globus pallidus and rostromedial substantia nigra to magnocellular cells in the ventral anterior and medial dorsal thalamus; the thalamus, in turn, projects back to DLPFC. Another parallel circuit projects from ACC to basal ganglia to medial dorsal thalamus and then back to ACC. LaBerge (1990, 1995, 1997, 1998; LaBerge et al., 1992) has demonstrated that cortico-thalamic-cortical feedback-feedforward loops can account for manifestations of attention. LaBerge (1999) speculates that cortical-subcortical loops may implement executive or

command aspects of attentional control such as those required for the operation of working memory. The frontal cortex must certainly be involved, but the basal ganglia and the thalamus—particularly the reticular nucleus surrounding the thalamus (Crick, 1984)—would be both well positioned and functionally capable of carrying out the gating functions needed for executive control. Dagenbach et al. (unpublished data) have demonstrated impairment on a variety of working memory tasks in five of six individuals with isolated thalamic stroke.

### **Maintaining Goals and Constraints on Action, Planning a Sequence of Subtasks**

Using fMRI, Koechlin et al. (1999) showed that maintaining a main goal in mind while performing concurrent subtasks selectively activated areas in PFFC (BA 10), bilaterally. This was distinct from activation associated with successively allocating attention between alternate goals—dual task performance—which produced more posterior frontal activation in SMA (BA 8) and DLPFC (BA 9). By contrast, Badre et al. (unpublished data) found that having to update two aspects of working memory concurrently (which of two counters was to be changed and what operation was to be performed on it), activated DLPFC (BA 9/46/47) whereas updating either of the component aspects alone activated areas in PFFC (BA 10: ventromedially for changing the counter; dorsolaterally for changing the operation). It is possible to resolve the apparent discrepancy by supposing that goals are maintained in PFFC whereas management of multiple goals is coordinated in DLPFC.

### **SUMMARY**

The field of neuroimaging of cognitive functioning is in its infancy and is developing rapidly. Broad, simplifying summaries are likely to be at once premature and rapidly out of date. Nevertheless, we will hazard such a summary. At least for verbal information, for spatial locations, and for visual objects, it appears that the working memory storage buffers are in posterior areas, proximal to the primary and secondary sensory areas. The buffers appear to be lateralized with verbal and object information stored primarily in left hemisphere, and spatial location in right. Maintenance of information in working memory appears to involve anterior cortex, particularly the ventral portions of PFC. Maintenance may be lateralized by the modality of the information. Subvocal rehearsal is an effective device for maintenance of verbal material, and certainly involves Broca's and premotor areas. Covert movements of attention may be used for rehearsal of spatial information, and they may activate homologous right hemisphere areas. Recent reports, however, have failed to find differences in activation in prefrontal cortex as a function of stimulus modality. Understanding of executive processes is still limited, but they certainly involve DLPFC and probably ACC. There are connections to subcortical structure such as basal ganglia and thalamus, and those structures may play an important role in executive memory processes. We can expect the rapid advances in our understanding of working memory to accelerate as neuroimaging becomes a more widely used approach.

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