2 Working Memory

The Multiple-Component Model

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FIVE CENTRAL FEATURES OF THE MODEL

(1) According to our view, working memory comprises multiple specialized components of cognition that allow humans to comprehend and mentally represent their immediate environment, to retain information about their immediate past experience, to support the acquisition of new knowledge, to solve problems, and to formulate, relate, and act on current goals.

(2) These specialized components include both a supervisory system (the central executive) and specialized temporary memory systems, including a phonologically based store (the phonological loop) and a visuospatial store (the visuospatial sketchpad).

(3) The two specialized, temporary memory systems are used to actively maintain memory traces that overlap with those involved in perception via rehearsal mechanisms involved in speech production for the phonological loop and, possibly, preparations for action or image generation for the visuospatial sketchpad.

(4) The central executive is involved in the control and regulation of the working memory system. It is considered to play various executive functions, such as coordinating the two slave systems, focusing and switching attention, and activating representations within long-term memory, but it is not involved in temporary storage. The central executive in principle may not be a unitary construct, and this issue is a main focus of current research within this framework.

(5) This model is derived empirically from studies of healthy adults and children and of brain-damaged individuals, using a range of experimental methodologies. The model offers a useful framework to account for a wide range of empirical findings on working memory.

There is broad agreement among the contributors to this volume that working memory refers to aspects of on-line cognition – the moment-to-moment monitoring, processing, and maintenance of information both in laboratory tasks and in everyday cognition. Our own definition of working memory is that it comprises those functional components of cognition that allow

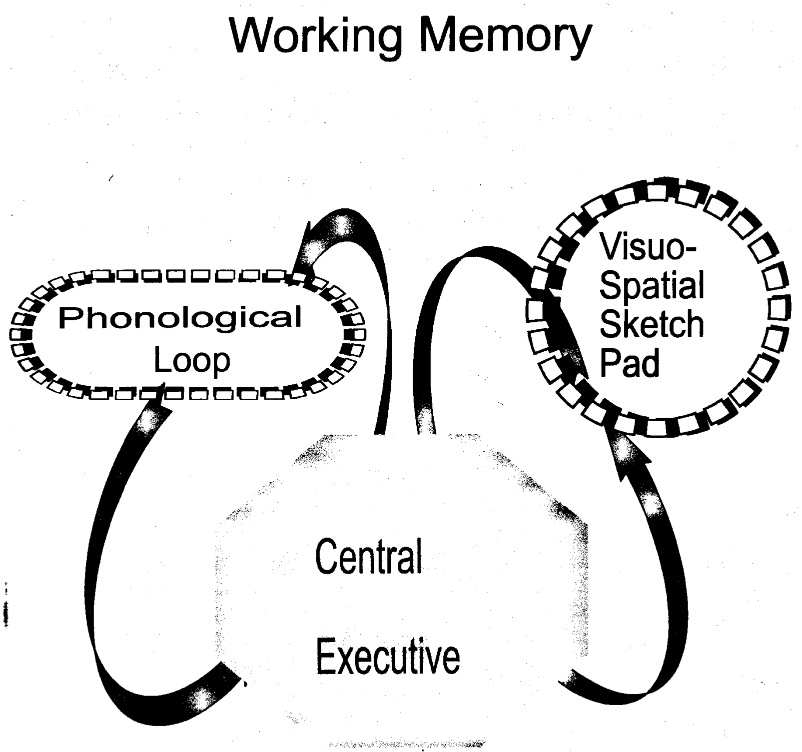

Figure 2.1. A schematic diagram of a multiple-component model of working memory (derived from Baddeley & Hitch, 1974).

humans to comprehend and mentally represent their immediate environment, to retain information about their immediate past experience, to support the acquisition of new knowledge, to solve problems, and to formulate, relate, and act on current goals.

Our theoretical approach has developed in the framework of working memory comprising multiple specialized subcomponents of cognition. The exact nature of these components is considered an empirical question, rather than something that forms an a priori assumption of the model. The original model proposed by Baddeley and Hitch (1974), shown schematically in Figure 2.1, comprises a *central executive* controlling mechanism and two subsidiary or "slave" systems, called the *phonological loop* and the *visuospatial sketchpad,* which are specialized for the processing and temporary maintenance of material within a particular domain (i.e., verbally coded information and visual and/or spatial information, respectively).

In this chapter, we outline our responses to each of the eight designated questions from the perspective of this model. The responses are generally organized according to the original scheme set by the editors (Shah & Miyake, Chapter 1, this volume). In writing the chapter, however, we became aware that our responses to some of the questions could be best answered within a single section, using the same arguments and evidence. Therefore, we have combined our discussion of the non-unitary nature of our model with that of basic mechanisms and representation, although the material relevant to both of these questions crops up throughout the chapter. Our response to the question on biological implementation of working memory is also provided throughout the chapter and illustrated with concrete examples in relevant sections. Table 2.1 presents a brief summary of our answers to each question.

Basic Mechanisms and Representations in Working Memory and the Unitary Versus Non-Unitary Nature of Working Memory

As the above overview indicates, our model of working memory is inherently non-unitary in nature. It comprises multiple specialized components, including the central executive and the two slave systems. The evidence supporting

Table 2.1. *Summary Responses to the Eight Questions from the Perspective of the Multiple-Component Model of Working Memory*

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(1) Basic Mechanisms and Representation in Working Memory
The multiple-component model consists of a central executive controller and two subsidiary systems specialized respectively for temporary storage of phonologically based material (the phonological loop) and of visuospatial material (the visuospatial sketchpad). The characteristics of these systems have been derived largely from empirical investigations. The phonological loop is further fractionated into a passive, phonological store and an active rehearsal system, whereas the visuospatial sketchpad has recently been fractionated into a passive visual cache and an active spatially based rehearsal system called the inner scribe.

(2) The Control and Regulation of Working Memory
The central executive offers the mechanism for control processes in working memory, including the coordination of the subsidiary memory systems, the control of encoding and retrieval strategies, the switching of attention, and the mental manipulation of material held in the slave systems (Baddeley, 1996). The central executive itself, however, is not equipped with the supplementary storage capacity. The detailed nature of the processes attributed to the central executive are derived empirically. The organization of these processes remains an open question and is the subject of ongoing empirical exploration.

(3) The Unitary Versus Non-Unitary Nature of Working Memory
Our model has an inherently non-unitary nature in that it comprises several specialized components, which can be further fractionated if such fractionation is adequately justified empirically. Even the central executive in principle may not be a unitary construct, but this is the subject of current work in this framework.

(4) The Nature of Working Memory Limitations
The components each have constraints commensurate with the specialist function that each provides, and these constraints may arise from capacity for activation or from capacity for rehearsal, or from capacity for complexity

of material, or from the extent to which they are supported by acquired strategies and prior knowledge.

(5) **The Role of Working Memory in Complex Cognitive Activities**
Our model offers a coherent account of the role of working memory in different domains of complex cognition, such as language comprehension, counting and mental arithmetic, syllogistic reasoning, and dynamic perceptuomotor control. All these complex cognitive tasks rely on a range of cognitive resources, and the multiple-component model and the associated dual-task methodology offer a fruitful framework for exploration of such tasks.

(6) **The Relationship of Working Memory to Long-Term Memory and Knowledge**
Temporary memory is influenced by information from long-term knowledge as well as the operation of the components of working memory. Although some have viewed working memory as an activated portion of long-term memory, such a view is probably an unhelpful oversimplification. We believe instead that working memory and long-term memory comprise two functionally separable cognitive systems. More specifically, a major role for working memory is retrieval of stored long-term knowledge relevant to the tasks in hand, the manipulation and recombination of material allowing the interpretation of novel stimuli, and the discovery of novel information or the solution to problems. Working memory also plays a major role in encoding into long-term memory the outcome of its operations.

(7) **The Relationship of Working Memory to Attention and Consciousness**
The central executive is thought to play an important role in the control of attention, although it is becoming clear that attentional control is not a unitary function, and the central executive is not the only system to contribute. The work of Norman and Shallice (1986) and, more recently, Posner (1995), has been used as a possible framework for the role of the central executive in attentional control. The executive does appear to offer a plausible account for some aspects of attention switching and of dividing attention. Our model also provides a useful way to study conscious awareness and its relation to working memory (Baddeley & Andrade, 1998).

(8) **The Biological Implementation of Working Memory**
The development of our model has relied in part on detailed studies of brain-damaged patients, and these studies have offered insights into the possible aspects of brain organization linked to the components of working memory. More recently, these neuropsychological studies have been supplemented by a range of neuroimaging techniques (Smith & Jonides, 1997). The lower part of the left parietal lobe appears to be associated with verbal short-term memory tasks, while the right posterior parietal lobe appears to be one of several anatomical locations linked with visuospatial working memory tasks. Some of the executive functions have been linked to the frontal lobes, although many tasks thought to involve the central executive may involve other areas of the brain as well.

the separability of these subcomponents of working memory is abundant, ranging from the selective interference effects found in normal adults in dual-task paradigms (e.g., Baddeley, 1986; Logie, 1995), through the patterns of selective sparing and impairments in brain-damaged patients (e.g., Della Sala & Logie, 1993), to the differential rates of developmental changes (or "developmental fractionation") observed among children (e.g., Hitch, 1990). We will discuss relevant findings supporting this multiple-component framework throughout this chapter.

Each of these components of working memory can be further fractionated if such fractionation is adequately justified empirically. Since the proposal of the original model, the phonological loop has been fractionated into a passive *phonological store* and an active *rehearsal process*. The phonological store represents material in a phonological code, which decays with time, whereas the rehearsal process serves to refresh the decaying representations in the phonological store, a distinction that is supported not only by experimental and neuropsychological findings (e.g., Baddeley, 1986) but more recently by neuroimaging data as well (e.g., Smith & Jonides, 1997). Similarly, the visuospatial sketchpad has recently been fractionated by one of us into a passive *visual cache* and an active spatially based system called the *inner scribe* (Logie, 1995). The evidence supporting this distinction will be reviewed shortly. As we will argue later in the "Control and Regulation of Working Memory" section, the central executive may also, in principle, not be a unitary construct, and a fractionation into different subcomponents or subprocesses is probably necessary (Baddeley, 1996).

With respect to the rehearsal mechanism for the two slave systems, we assume that memory traces can be set up, using processes that overlap with those involved in perception, and can be actively maintained using processes related to those involved in action or response production. In the case of the phonological loop, these processes are assumed to involve aspects of the systems necessary for speech perception and for assembling speech output programs. In the case of the visuospatial sketchpad, the nature of the rehearsal mechanism is less clear, although one of us has argued that preparation for actions, handled by the inner scribe, might subserve maintenance functions for spatially based information, whereas some aspects of image generation might support visual retention (Logie, 1995). Immediate memory performance is a joint function of these two subprocesses of storage and rehearsal. However, whereas we assume that initial activation is essential for working memory performance, active rehearsal is regarded as an optional means of enhancing performance, and hence is not obligatory (Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996).

The Nature of Working Memory Limitations

The subcomponents of our model are thought to have constraints commensurate with the specialist functions that each provides. In each case, however, we tend to have assumed a structure or set of structures that depends on activation, with both the amount and duration of activation being limited. In this section, we review some relevant evidence on this issue for each of the two slave systems.

Limitations in the Phonological Loop

We assume that individual differences in the phonological loop capacity reflect the amount of memory activation available, partly as a result of genetic factors. In addition, some variation in memory activation may result following brain damage. For example, patients with impaired verbal short-term memory (STM) appear to be able to encode material quite normally, in the sense of perceiving words and sentences, but the trace of such perceptual processing does not persist, indicating a lack either of adequate activation or of maintenance. Such patients, however, often have a normal capacity for speech production (Vallar & Baddeley, 1984), suggesting that the principal problem is not one of response production and, hence, probably not of incapacity to rehearse.

In addition to the limits on degree of activation, we also assume that subjects may differ in their rehearsal capacity. In the case of the phonological loop, this capacity appears to reflect one's ability to set up and run speech output programs, but does not require that such programs be explicitly realized through articulatory output. Our reason for this assumption is that dysarthric patients who have lost the capacity to control their peripheral speech musculature nonetheless show normal rehearsal patterns (Baddeley & Wilson, 1985; Della Sala, Logie, Marchetti, & Wynn, 1991), whereas dyspraxic patients who have lost the capacity to set up the appropriate speech motor programs have difficulty in rehearsing (Caplan, Rochon, & Waters, 1992).

A related issue that has evoked considerable research concerns the developmental changes in the phonological loop capacity. Nicolson (1981) first demonstrated a close association between an age-related increase in memory span and increase in speed of articulation, leading to an extensive series of studies exploring the possibility that the development of span can be entirely attributed to faster rehearsal (e.g., Hulme, Thomson, Muir, & Lawrence, 1984). Although this hypothesis initially appeared to fit the data remarkably well, subsequent research has suggested that this view is probably an oversimplification, with rehearsal in young children being qualitatively different from that found in older children and adults (see Gathercole & Hitch, 1993, for a review).

In the case of adults, one of the principal means of studying verbal rehearsal has been through the word length effect, whereby memory span is a direct function of the spoken length of the to-be-recalled items (Baddeley, Thomson, & Buchanan, 1975). In these initial studies, subjects were instructed to respond in writing and to limit their response to the first three letters of each word, so as to equate the amount of output interference. In studies where this precaution is not taken, an additional major factor is the increased delay engendered by the spoken recall of longer words, a point amply demonstrated by Cowan et al. (1992). The word length effect, however, is not entirely due to output delay because the effect is still present (albeit smaller) when performance is measured by a probe technique (Henry, 1991) or a recognition procedure (Baddeley & Wilson, 1985; Della Sala et al., 1991).

What then is our current position on word length and rehearsal? We still believe that rehearsal operates in real time and that longer items will take longer to rehearse, allowing more forgetting to occur. We accept, however, that, under standard conditions, performance will reflect both rehearsal and output delay effects. In short, we stand by the proposed phenomena of real-time rehearsal and trace decay, but acknowledge that the contribution of various factors to the word length effect may well vary depending upon the circumstances (Logie et al., 1996).

TRACE DECAY OR OUTPUT INTERFERENCE? As Cowan, Wood, Nugent, and Treisman (1997) have pointed out, the differential output delay engendered by recalling words differing in length could represent either spontaneous fading of the memory trace or interference from the intervening material. Baddeley et al. (1975) attempted to test this issue by comparing the recall of words that were matched for number of phonemes, but differed in spoken duration, contrasting long-duration words (such as *Friday* and *harpoon*) with shorter-duration ones (such as *bishop* and *wicket*). They observed that words with longer duration led to poorer performance. Cowan et al. (1997) challenged this conclusion, arguing that the longer-duration words have stresses on both syllables, whereas the shorter-duration words have only one stress. In a rather complex study in which subjects were trained to vary the pronunciation of monosyllabic and disyllabic words on instruction and were required to recall in reverse order, they report evidence of both a negative effect of duration and a positive effect of complexity (see Cowan, Chapter 3, this volume, for more detailed discussions of this study). There appears to be disagreement among the authors as to the interpretation of these results, with Cowan wishing to continue to support a trace decay assumption, whereas Treisman argues for an interference interpretation. It should be noted, however, that this interference interpretation is a rather unusual one in that it appears to assume that similarity does not influence interference, but duration does.

Evidence that the word length effect is not specifically an output interference phenomenon comes from an earlier study by Baddeley and Hull (1979), in which seven-digit sequences were followed by either a prefix that the subject had to speak before recalling or by a stimulus suffix that required no response. The prefix/suffix ranged in length from one to five syllables. The results showed a clear effect of length, which was broadly equivalent whether the subject was required to speak the item or merely listen to it. It is important to note that the effect in question operates throughout the list. This effect thus differs from the standard suffix effect, which impairs recall of the last item.

Baddeley (1986, pp. 94–95) presents further evidence for a decay interpretation of this through-list suffix effect. In this study, subjects were presented with sequences of nine digits and required to recall by writing the sequence on either the left- or right-hand side of their response sheet. The instruction "left" or "right" was always presented immediately after the last digit, resulting in a brief delay during which the instruction was processed. In a second condition, the instruction was again given, but subjects were informed that the instructions would always alternate "left, right, left, right," and so on, making the information redundant. Subjects' recall performance showed a consistent advantage when the prefix was redundant over when the instruction information had to be processed. Such a result, however, left at least one alternative to the temporal delay hypothesis, namely that forgetting occurred because of interference from the requirement to process the response instruction, not from decay during the temporal delay per se. These two hypotheses were tested in a further experiment in which the instruction was presented between the eighth and ninth digits, allowing the response decision to be made *before* the last digit and hence removing the delay, but still exposing retention of eight of the nine digits to potential interference. The informational disruption hypothesis thus predicts substantial interference, whereas the temporal delay hypothesis would predict that the difference between the two conditions would vanish. The results matched the latter prediction, hence supporting the hypothesis that forgetting occurs because of the temporal delay. Thus, like Cowan (Chapter 3, this volume), we continue to assume trace decay, but would accept that its detailed nature and time course remain to be explored.

Limitations in the Visuospatial Sketchpad

Measures of visuospatial working memory have focused on memory for spatial movement and for visual patterns. The thrust of much of the evidence now available points to the dissociation between a capacity for retaining visual patterns (the visual cache; Logie, 1995) and that for retaining sequences of movements (the inner scribe). For example, a number of dual-task studies demonstrated a disruptive effect of concurrent movements on the retention of spatial patterns (Baddeley & Lieberman, 1980; Logie, Zucco, & Baddeley, 1990; Smyth & Pendleton, 1989) as well as a disruptive effect of concurrent or interpolated viewing of irrelevant, changing visual material on the retention of visual information (Logie, 1986; Quinn & McConnell, 1996). Logie and Marchetti (1991) demonstrated this double dissociation in a single study, showing that retention of spatial patterns, but not visual information (shades of color), was disrupted by arm movements during a retention interval, whereas retention of visual information, but not spatial patterns, was disrupted by a visual interference task interpolated between presentation and retrieval. Further evidence comes from a recent developmental study (Logie & Pearson, 1997). In this study, children aged 5, 8, and 11 were tested on their memory span for recognition and recall of square matrix patterns and of movements to a series of targets (the Corsi blocks test). Within each age group, the span measures for patterns correlated poorly with span for movements. Furthermore, while performance on both types of task improved with age, span for patterns improved much more rapidly across age than did span for movement sequences. Such developmental fractionation indicates that the capacity of these subsystems develops at different rates.

Given that there is an empirically based case for separate subcomponents within the visuospatial sketchpad, this visual versus spatial distinction then raises the issue as to what constrains the capacity of each subsystem. Although the precise nature of the mechanisms underlying the capacity limitations for spatial and visual information is not clear yet, recent work has revealed some important factors that contribute to the capacity limits of each subsystem.

As for the spatial subcomponent (or the inner scribe), we know that retention of movement or of paths between objects and locations does not depend on visual perceptual input. The relative physical location of objects can be determined by hearing, by touch, or by arm movement as well as by vision, and few would dispute that the blind can have spatial representations (Kerr, 1983; Vecchi, Monticellai, & Cornoldi, 1995). We also know that memory for movement sequences can be affected by complexity, such as dimensionality. Cornoldi, Cortesi, and Preti (1991), for example, asked subjects to imagine paths through two-dimensional (e.g., 5 × 5 squares) and three-dimensional (e.g., 3 × 3 × 3 blocks) square matrices. Most subjects found the three-dimensional matrix more difficult than the two-dimensional one, despite the fact that the total number of squares or blocks is approximately the same in each case. However, the detailed characteristics of the limitations on memory for movement sequences have yet to be explored fully.

As for the visual subcomponent (or the visual cache), one important capacity-constraining factor seems to be the visual similarity of to-be-maintained items. For example, Hitch, Halliday, Schaafstal, and Schraagen (1988) found visual confusion errors occurring in young children's recognition memory. The children in these studies were shown a series of pictures, some of which were visually similar to one another (such as a brush, a rake, and a pen), while other items were visually distinct (such as a pig, a ball, and a pen). Five-year-old children showed poorer recognition memory for items from the visually similar set. With older children, the effect of visual similarity also appeared, but only if they were required to suppress verbalization (via concurrent articulation of well-known words or syllables, such as "the, the, the. . .") and thereby forced to rely more heavily on visual rather than verbal codes (Hitch, Woodin, & Baker, 1989). Analogous visual similarity effects for familiar letter or digit stimuli have also been found among adults, both in healthy normals under articulatory suppression conditions (Walker, Hitch, & Duroe, 1993) and in patients with severe phonological loop impairments, such as Patient KF

(Shallice & Warrington, 1970), whose memory span errors in visual presentation tended to be visual in nature. Furthermore, using visually complex Chinese characters that were not familiar to their subjects and thereby forcing them to rely on visual codes, Hue and Ericsson (1988) found visual similarity effects in the immediate recall of these Chinese characters. These studies all support the idea that visual similarity between the items being retained in this system leads to a reduction in capacity. This visual similarity effect (as well as an analogous phonological similarity effect associated with the phonological loop; Conrad, 1964) is essentially equivalent to the notion of similarity-based interference discussed by Young and Lewis (Chapter 7, this volume).

Another capacity-limiting factor for visual pattern memory may be the number of items. For example, Phillips and Christie (1977) and, more recently, Walker et al. (1993) reported a one-item recency effect in recognition memory for a sequence of square matrix patterns or random block patterns. Similarly, Broadbent and Broadbent (1981) showed analogous recency effects for abstract wallpaper patterns or sets of irregular abstract line drawings. This kind of evidence points to the suggestion that visual temporary memory may be able to hold only a single pattern, but the visual complexity of the pattern or the similarity of the pattern elements to one another may constitute additional limitations on the capacity of the system.

The Control and Regulation of Working Memory

As with the original Baddeley and Hitch (1974) model, we continue to assume that working memory is controlled by a central executive. The concept of the central executive, however, has undergone a number of significant changes over the past 20 years. In particular, the original model assumed that the central executive comprised a pool of general-purpose processing capacity that could be used to support either control processes or supplementary storage. We have subsequently abandoned the assumption that the central executive itself stores information, proposing instead that any increase in total storage capacity beyond that of a given slave system is achieved by accessing either long-term memory (LTM) or other subsystems (for a similar proposal, see Ericsson & Delaney, Chapter 8, this volume). There are a number of reasons for this change, some theoretically driven and others empirically driven.

From a theoretical viewpoint, we were unhappy about giving the central executive the capacity to supplement and, hence, mimic the capacities of the slave systems or indeed in principle any other memory system. We felt that this practice would make the central executive system simply too powerful and too flexible to be productively investigated. As some chapters of this volume propose (Cowan, Chapter 3; Engle, Kane, & Tuholski, Chapter 4), separating out control and storage processes seemed to offer a better chance for making progress.

From an empirical viewpoint, the motivation for revising our initial assumptions reflects growing evidence that working memory can utilize temporary storage in systems other than the two slave systems. One obvious example is the recency effect, which we have suggested represents the priming of representations in LTM, a relatively automatic process, coupled with a specific and active retrieval strategy (Baddeley & Hitch, 1977, 1993). We suspect that this process can extend well beyond the priming of individual lexical items up to the activation of relatively high-level semantic structures such as complex schemata. An interesting source of evidence for such a view comes from the observation that certain densely amnesic but otherwise intact patients are nevertheless capable of demonstrating excellent immediate recall of a prose passage, coupled with an almost complete absence of delayed recall (Wilson & Baddeley, 1988). We assume that this capability reflects the process of comprehension, whereby schemata are activated and maintained by the central executive. In a normal subject, this would lead to encoding and storage in LTM, whereas in a profoundly amnesic patient, once activation by the central executive is removed, performance rapidly declines. A similar and much more articulated view of this issue was proposed by Ericsson and Kintsch (1995) (see Ericsson & Delaney, Chapter 8, this volume).

Another empirical reason for not giving the central executive a supplementary storage capacity comes from our recent work involving the processing and storage demands associated with the performance of complex working memory tasks (Logie & Duff, 1996). One widely used verbal measure, Daneman and Carpenter's (1980) reading span task, for example, requires subjects to read a series of sentences and maintain the final word of each for later recall (see Engle et al., Chapter 4, this volume, for further discussions on working memory spans). In general, Daneman and Carpenter (1980) suggest that this recall measure of the sentence final words reflects the operation of executive processes in working memory, rather than or besides the functioning of the slave systems like the phonological loop alone. The underlying assumption, then, is that as memory demands increase, there is less capacity available for processing and vice versa.

One possible alternative view is that the working memory measure involves not only on-line processing and control but also short-term verbal memory, and that these cognitive demands are supported by separate components of working memory (i.e., the central executive and the phonological loop, respectively). Supporting this alternative view, Engle et al. (Chapter 4, this volume) report an elegant analysis of the partial correlations arising from putative different components of the task, suggesting that temporary storage (handled by the phonological loop) and controlled attention (handled by the central executive) each make semiindependent contributions to individual variations in the performance of complex fluid intelligence tasks.

In our recent work (Logie & Duff, 1996), we have attempted to examine more closely the possible separate cognitive demands of processing and storage. In particular, we have examined the extent to which increasing processing demands results in poorer performance on the storage elements of the task. In one of the experiments, subjects were given a processing task, a storage task, and a processing-and-storage task. The processing task required a verification of a series of simple sums within a 10-s period. Subjects were first given a two-sum trial (e.g., 9 + 6 = 15 or 5 + 8 = 12), where each sum was presented for 5 s. Following correct verification of both sums, three sums were presented for 3.33 s each, followed by four sums (2.5 s each), and so on, until subjects were no longer able correctly to verify all of the sums presented in the 10-s period. In the storage task, these same subjects were tested for immediate serial recall span for sequences of unrelated words. The subjects were then required to perform both the processing and storage elements of the task with each verification sum shown along with an unrelated word. The main results of the study were that a demanding storage task had virtually no impact on the capacity for arithmetic verification and also that a demanding verification task had little effect on span for words. Three other experiments using similar procedures showed similar patterns of results, offering little support for the view that processing and storage demands compete for a single resource. A more plausible explanation is that the words were retained in a temporary verbal store such as the phonological loop, while the executive was involved in conducting the verification task.

Is the Central Executive Merely a Homunculus?

One problem with postulating a control structure like the central executive is that such a model simply postulates a homunculus, a little person who makes all the awkward decisions in some unspecified way and, hence, that it adds nothing in explanatory value. This general issue is discussed in detail elsewhere (Baddeley, 1996; Baddeley & Della Sala, 1996) and, hence, the arguments will be summarized only briefly.

Our previous research has focused primarily on the structure and the functions of the two slave systems (Baddeley, 1986; Logie, 1995), which were considered more tractable than the central executive. We believe that this research strategy has already proved its value in terms of the progress made in understanding both the phonological loop and the visuospatial sketchpad. We fully accept, however, that it is not satisfactory to simply leave the central executive as a useful ragbag to contain all the phenomena that cannot be readily accounted for otherwise. In an attempt to make progress, we began a few years ago to postulate some of the processes that would have to be performed by any adequate central executive.

One of these processes concerns the capacity to control and coordinate the two slave systems. We devised a series of tasks in which a slave system and the central executive were used independently and in combination. For example, we found that the dual-task condition produced particularly marked decrements in patients suffering from Alzheimer's disease (Baddeley, Bressi, Della

Sala, Logie, & Spinnler, 1991; Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986) and in a specific subsample of patients with frontal lobe damage (Baddeley, Della Sala, Papagno, & Spinnler, 1997). We have subsequently begun to postulate a number of other executive functions, including the capacity to focus attention, to switch attention, and to activate representations within LTM (see Baddeley, 1996, for more detailed discussions on these executive functions).

We do not regard these as the only functions that are served by the central executive. We leave open to empirical investigation the question of whether they are indeed separate functions or might possibly reflect different operations of a smaller number of underlying control processes. We also leave open the possibility that many such subprocesses might reflect the amount of some common capacity such as excitation or inhibition. Finally, we can at present see no reason for taking a strong view on whether the central executive will ultimately prove to be a system within which a range of equally important control processes interact in a quasiautonomous way, with overall control forming an emergent feature, or whether there is a hierarchy of such processes with one dominant controller. In short, we leave open to investigation the question of whether the central executive resembles an organization run by a single chairperson or one governed by the collective wisdom of a committee of equals (see Barnard, Chapter 9, this volume, for a conception of this latter view of the central executive).

Clearly, for anyone wishing to simulate the working memory model, our extreme lack of specification must be a source of frustration. We feel, however, that simply making a guess on all the points discussed would have a vanishingly small chance of producing an accurate model of working memory. In addition, the formulation we propose has the major advantage of setting out a series of empirically tractable questions, the answers to which are likely to be of direct relevance to any adequate model of executive control.

The Role of Working Memory in Complex Cognitive Activities

As is clear from our discussion so far and also from other chapters of this volume, working memory plays a crucial role for complex cognitive activities such as language comprehension, mental arithmetic, and reasoning. All these cognitive activities require the moment-to-moment monitoring, processing, and maintenance of task-relevant information, which, as we argued in the last section, are supported by different components of working memory. Therefore, as will become clear shortly, any complex cognitive tasks, regardless of content domain, require the involvement of multiple components of working memory and the dynamic coordination of activities among them. The specific studies we review in this section also help to specify the precise role that each component plays in each specific complex cognitive task.

Language Comprehension

There has been considerable investigation into the role of working memory in this area (see Gathercole & Baddeley, 1993, for a more detailed review). The phonological loop might reasonably be considered to form a major bottleneck in the process of spoken language comprehension. Such a view was, for example, proposed by Clark and Clark (1977), who assumed that the syntactic analysis of a sentence required it to be held in verbal STM. This view would predict that the comprehension limits of a patient with an STM deficit would be set by the length of sentence that could be held in memory (typically, a 6-word sentence for such patients). In general, this is not the case, however. STM patients typically show only relatively minor comprehension problems, unless they are required to process sentences for which comprehension depends upon retaining the surface structure of the beginning of the sentence across many intervening words (see Vallar & Shallice, 1990, for a review).

A broadly similar picture emerges from studies of the role of the phonological loop in comprehension by normal subjects, as reflected in studies using techniques such as articulatory suppression to disrupt the operation of the phonological loop. Both articulatory suppression and phonological similarity do impair performance on certain types of reading task, particularly those involving detection of errors of word order (Baddeley, Eldridge, & Lewis, 1981), but the effects on comprehension per se appear to be relatively slight. It remains possible that there may be certain situations or types of material for which phonological coding is particularly important (possibly for the kind of prose that appears in legal documents, where the precise word order is important and the semantics obscure), but, to the best of our knowledge, even this has not yet been demonstrated.

There has been considerably less work on the role of the visuospatial sketchpad in comprehension. It seems possible, however, that reading may well depend on the capacity to hold and maintain some form of visuospatial framework. Brooks (1967), for example, showed that the act of reading may interfere with the temporary storage of imaged material, presumably through the operation of the sketchpad. Similarly, Eddy and Glass (1981) demonstrated that reading while attempting to verify high-imagery sentences resulted in poorer performance than when subjects listened to those same sentences. Some comprehension tasks may also depend on the setting up of some form of visuospatial representation, again involving the sketchpad. Haenggi, Kintsch, and Gernsbacher (1995), for example, demonstrated that the construction of spatial mental models from text might depend on visuospatial capacity.

As suggested earlier, we assume that the central executive plays an important role in comprehension (Gathercole & Baddeley, 1993). The executive is assumed to activate representations in LTM extending up from individual words and concepts to complex schemata. In a normal subject, the internal representation or model constructed by the central executive will result in the registration of that representation in long-term episodic memory, a process that does not adequately occur in the case of amnesic patients. We assume that the capacity to comprehend a particular passage will be determined both by the existing representations in LTM and by the capacity of the central executive to activate and combine such representations into a coherent mental model, which can then be consolidated into LTM (see O'Reilly, Braver, & Cohen, Chapter 11, this volume, for a similar proposal). Consistent with this view, an intelligent but densely amnesic patient can comprehend but not store a complex passage (Wilson & Baddeley, 1988), whereas patients with Alzheimer's disease who demonstrate an impairment in executive processes cannot even create the initial representation, performing poorly on both immediate and delayed recall.

Counting and Mental Arithmetic

Despite the fact that much of basic arithmetic skill involves automatic access to solutions of well-practiced arithmetic operations, recent studies convincingly demonstrate that working memory plays important roles in both counting and mental arithmetic.

COUNTING. The existing evidence suggests that, in addition to knowledge of the counting sequence and counting heuristics, counting requires temporary storage of the running total. This keeping track of the running total seems to be handled by the phonological loop (Hitch, 1978; Logie & Baddeley, 1987). For example, in a study by Nairne and Healy (1983), participants were required to orally count backwards. Errors in this relatively simple task were rare, but one type of systematic error concerned subjects' omitting numbers with repeated digits (e.g., *88*, *66*). The authors demonstrated that such repeated digit errors were based on phonological confusions between repetition of the decade prefix (*eighty*, *sixty*) and the second digit (*eight*, *six*), suggesting the involvement of the phonological loop (particularly, the phonological store) in counting. In some of our own studies (Logie & Baddeley, 1987), we examined counting of items in stimulus arrays or of event sequences, using the articulatory suppression technique. The stimulus arrays comprised from 1 to 25 dots presented at random positions on a computer screen, with subjects counting the number of dots as rapidly and as accurately as possible. The event sequence task involved counting the number of occasions on which a square appeared, at irregular intervals (400 to 900 ms), in the center of a computer screen. For both array counting and event counting, concurrent articulatory suppression resulted in a substantial number of errors, and the number of errors increased as the number of items or events increased. Counting performance, however, was not disrupted simply by the requirement to carry out any secondary task, because concurrent hand tapping failed to disrupt performance. These results strongly support the idea that the phonological loop is a highly plausible candidate for keeping track of a running total in counting. In addition to the phonological loop, the central executive may also play an important role in counting under certain circumstances, as Engle et al. (Chapter 4, this volume) report in their chapter.

MENTAL ARITHMETIC. Mental arithmetic is a complex skill that seems to require different components of working memory (Ashcraft, 1995; Logie, Gilhooly, & Wynn, 1994). More specifically, it appears to rely on temporary storage of partial solutions (primarily, the phonological loop function) as well as the application of algorithms for calculation and estimation (primarily, the central executive function).

In a recent study (Logie et al., 1994), for example, we used a dual-task methodology to examine the role of the phonological loop in mental arithmetic. We used cumulative addition of a series of two-digit numbers (e.g., 13 + 18 + 24 + 17 + 48 + 33 = ?) in this study, a task that was unlikely to be highly practiced and, hence, required subjects to keep track of the cumulative totals until responding with a final total. The results indicated that, with both auditory and visual presentation of the numbers, articulatory suppression as well as irrelevant background speech resulted in a substantial increase in the number of errors, whereas concurrent tapping did not. This pattern of results strongly points to a key role for the phonological loop in mental arithmetic.

An interesting finding from this study that illuminates the role of the central executive was that, whereas we observed a significant increase in the number of error totals with articulatory suppression, participants could still generate reasonable approximations: The mean error responses were within 6% of the correct total. This relatively intact approximation ability suggests that participants had a means to circumvent some of the disruptive effects of articulatory suppression or irrelevant speech. In the case of mental arithmetic, this means that there may be learned strategies that draw on well-learned sums. For example, the correct total for the sum 18 + 19 + 23 may not be available immediately, but the total for 20 + 20 + 20 is likely to be. Therefore, participants could guess that the answer to the former sum would be close to 60 without having to precisely keep track of running totals. As such, one suggestion is that the central executive is responsible for selecting and implementing such calculation heuristics.

To investigate this possible role of the central executive, we used a secondary task thought to disrupt strategy deployment, namely oral random generation (Baddeley, 1966a). This task involves subjects repeating aloud a series of letters of the alphabet selected in as random a fashion as possible. The cognitive demands of this task are thought to stem from the need to keep track of the frequency with which individual letters of the alphabet have been generated and to inhibit the production of well-learned or stereotyped sequences such as a-b-c-d-e. This inhibition of what are thought to be largely automatic processes is considered a form of executive or supervisory function. (Note that this task also disrupts the functioning of the phonological loop because of the continuous production of verbal outputs.) The effects of concurrent random generation on mental arithmetic are clear-cut. Random generation resulted in mean error rates of around 40%, and a number of participants even found it impossible to perform mental arithmetic at the same time. Moreover, error responses were poorer approximations to the correct totals than was found with articulatory suppression and irrelevant speech.

Taken together, these results point to the idea that mental arithmetic relies on the phonological loop for temporary storage, possibly that of partial solutions, and subvocal rehearsal of running totals. It also relies on the central executive for access and execution of computational algorithms or heuristics.

Syllogistic Reasoning

Syllogistic reasoning comprises the presentation of two related statements that are assumed to be true, for example, *All baritones are singers; all singers are human.* The subject's task is to determine what conclusion, if any, can be drawn from relating the two statements (Answer: *All baritones are human*). There is a large range of such syllogistic argument combinations with variation in the quantifiers (e.g., *all, none, some*) and the inclusion of negatives (e.g. *Some tenors are not men; all tenors are human*; Answer: *Some humans are not men*). This last example is rarely solved correctly, particularly when the syllogistic arguments are presented in an abstract form (e.g., *Some B are not A; all B are C. Therefore?*). The question, then, is why some problems are harder than others and how working memory might be implicated in the solving of these syllogistic reasoning problems (see Young & Lewis, Chapter 7, this volume, for a discussion of an alternative perspective on the role of working memory in syllogistic reasoning).

Johnson-Laird (1983; Johnson-Laird & Byrne, 1991) has argued that some forms of syllogistic reasoning require the formation of two or more mental models and that additional mental models place additional demands on working memory, resulting in slower or less accurate conclusions. Alternative explanations suggest that most participants do not follow the rules of formal logic in performing these tasks and instead adopt heuristics that result in above-chance performance. The *atmosphere hypothesis* (Woodworth & Sells, 1935), for example, postulates that participants derive their conclusion from the quantifiers in the two initial statements or premises (e.g., including the quantifier "some" in the conclusion if one or both premises contain "some"). Alternatively, the *matching hypothesis* (Wetherick, 1989) postulates that subjects are thought to generate a conclusion that is similar to the more conservative of the two premises.

Crucial to our current discussion is that the mental model hypothesis predicts a heavy demand on working memory (particularly for those problems that require the construction of multiple models), whereas both the atmosphere and matching hypotheses predict a low demand on working memory for the selection and implementation of heuristics aimed at producing an acceptable level of performance. Therefore, while the mental model hypothesis predicts a significant impact of concurrent tasks on reasoning performance, the other two hypotheses predict little such impact. Moreover, if there are any participants who do happen to perform above the level expected for the atmosphere or matching hypothesis, then it is likely that they are generating mental models and would be more prone to disruption from secondary tasks.

In a series of studies, we have investigated these predictions regarding the effects of concurrent tasks, most notably articulatory suppression and random generation (Gilhooly, Logie, Wetherick, & Wynn, 1993). Performance in single-task conditions fitted most closely with the predictions of the matching hypothesis, and this result also held when syllogistic reasoning was combined with articulatory suppression, which caused no disruption in reasoning performance. However, concurrent random generation did result in a significant drop in reasoning performance, although the absolute drop in performance was quite small, and the performance level remained well above chance. That is, working memory appeared to play only a minor role in performance of syllogistic reasoning tasks for many subjects.

This finding, however, was most likely due to the fact that most subjects did not reason logically and therefore did not place heavy demands on working memory. The small effect of random generation points to some role of executive processes in the implementation of the matching heuristic that appeared to be adopted by most subjects. In more recent, as yet unpublished studies (Gilhooly, Logie, & Wynn, 1998), we have explored the effects on dual-task performance of individuals who have been trained on syllogistic reasoning. Subjects were given extensive practice with different forms of the task, and their performance was later tested on a new set of problems. Most of the participants successfully improved their performance, and subsets of participants who performed particularly well or particularly poorly (but well above chance) completed both single- and dual-task conditions. Those subjects who performed poorly were largely unaffected by the secondary tasks. However, those subjects who had produced the highest scores following training were especially vulnerable to the disruptive effects of random generation. That is, the training seemed to have resulted in better performance at the expense of an additional load on the executive resources of working memory. These results are reminiscent of the recent observation (Rosen & Engle, 1997) that high-working-memory-span subjects tended to show a clearer decrement following a concurrent load than low-span subjects in a demanding memory retrieval task that required the involvement of the central executive or controlled attention.

Dynamic Cognition and Complex Perceptuomotor Control

The multiple component model of working memory has also been found to be useful in studying the cognitive effects of training in complex dynamic tasks. We used dual-task procedures to investigate the cognitive resources involved in a complex computer game known as Space Fortress (Logie, Baddeley, Mane, Donchin, & Sheptak, 1989). The game involved a high level of perceptuomotor control of a "space ship," which was maneuvered around a computer screen using a joystick. The game also involved accurate timing of responses, a verbal STM load, and the development of long-term and short-term strategies. Space Fortress required around 10 h of practice to reach a reasonable level of performance. The general aim of this research was to determine whether the Space Fortress task could be fruitfully split into a number of subcomponent skills and to examine the changes in demands on working memory following extensive training (25 h or more). We used a range of secondary tasks each thought to draw on specific components of working memory.

Early in training, we observed that game performance was equally impaired by concurrent verbal tasks and by concurrent visuospatial tasks, each of which involved heavy demands on temporary storage and a small degree of processing (Brooks, 1967). In contrast, concurrent repeated and alternate tapping of the feet had very little effect on performance. When the participants had reached a much higher level of expertise on the game, a rather different pattern of dual-task disruption emerged. Instead of across-the-board impairment, the concurrent visuospatial tasks disrupted only those game parameters that were linked to perceptuomotor control, while the verbal secondary tasks impaired parameters linked with verbal STM. Moreover, the tapping task, which previously had shown little effect when players were less experienced, appeared to cause considerable disruption of game performance. This disruption arose from poor motor control of the joystick and other motor responses required for game performance.

These results seem to suggest that the general cognitive load was very high in the early stages of the game, while motor control was poorly deployed. As a result, any secondary cognitive load was sufficient to disrupt performance. However, with the acquisition of expertise came the use of specialized rather than general purpose resources and greater demands on more finely tuned perceptuomotor control. Such a change in working memory demands is perfectly in line with Ackerman's (1988) theory of complex skill acquisition, which postulates that as one's skill level increases, the primary factor that constrains performance changes from general fluid intelligence through domain-specific perceptual speed to psychomotor abilities.

This work (Logie et al., 1989) represents one of the few attempts to use working memory in complex dynamic environments and, because initial work on this topic proved promising, it is an area that merits significantly more attention.

Summary

The studies we reviewed in this section clearly demonstrate that complex cognitive tasks rely on a range of cognitive resources and implicate multiple components of working memory. They also highlight the utility of the multiple-component model and the associated dual-task methodology as a basis for cognitive task analyses.

The Relationship of Working Memory to Long-Term Memory and Knowledge

As we have already made clear, we assume that one important feature of the central executive is to activate and integrate representations in LTM. In this respect, our views have a good deal in common with Ericsson's proposal of long-term working memory (Ericsson & Delaney, Chapter 8, this volume; Ericsson & Kintsch, 1995) and Cowan's proposal of virtual STM (Cowan, Chapter 3, this volume). Does this then mean that working memory is simply the currently activated portion of LTM? Although we believe that such a formulation is defensible and has the attraction of apparent conceptual simplicity, we regard it as an unhelpful oversimplification and believe that working memory and LTM comprise two functionally separable cognitive systems. Below, we characterize the relationship between the two memory systems and provide illustrative evidence for the separability of each of the slave systems from LTM.

The Phonological Loop

There is considerable evidence that long-term knowledge has an influence on the performance of verbal STM tasks. For example, memory span for familiar words is longer than for nonsense syllables, and memory span for words in sentences is longer (15–16) than for unrelated words (5–6) (Baddeley, Vallar, & Wilson, 1987). In addition, nonwords that approximate English result in better immediate recall than those that do not (e.g., Gathercole & Baddeley, 1989), and familiarizing subjects with nonwords increases serial recall capacity (Hulme, Maughan, & Brown, 1991). Furthermore, as discussed in the chapter by Ericsson and Delaney (Chapter 8, this volume), the superior memory performance that often underpins expert performance is typically based on the temporary utilization of gradually acquired schemata.

One apparently simple interpretation of this wide range of data is to propose something like a pandemonium model (Selfridge, 1959) in which acoustic information is encoded and processed through a series of levels, beginning with isolated speech sounds, moving up to phonemes, then syllables, which in turn may map onto sublexical and lexical units. Where appropriate, these may activate higher level syntactic and semantic structures, which in turn may be categorized in terms of semantic schemata. The level at which the encoding stops will be determined by the capacity of the system to provide useful and meaningful chunks (Miller, 1956). In the case of complex nonwords, these chunks are likely to be sublexical units, with letter sequences approximating to the native language of the subject offering a greater capacity for chunking than would be possible with less familiar phonetic sequences (Gathercole, 1995). In the case of words, the already existing lexical representations will help performance, but where the same set of unrelated words is used repeatedly, as in the typical memory span procedure, the capacity to form meaningful chunks will be minimal; moreover, lexical priming is likely to offer little help in storing serial order, forcing the subject to depend upon phonological cues and minimizing any effects of semantic similarity within the set (Baddeley, 1966b). However, when the material allows semantic and syntactic links to be readily formed between the items, either by selecting combinations of nouns and adjectives that are readily compatible (Baddeley & Ecob, 1970) or by using material that approximates to the sentential structure of English (Miller & Selfridge, 1950), subjects will extend the amount of material held by incorporating more items in each individual chunk (Miller, 1956). Thus, the available evidence suggests that STM performance reflects the activation of those long-term representations involved in perceiving and comprehending spoken language.

There is also considerable evidence that the phonological loop has an influence on long-term phonological learning. For example, patients with STM deficits have major impairments in the capacity for new phonological learning (Baddeley, Papagno, & Vallar, 1988), and normal subjects show impairment in new phonological learning if performing concurrent tasks that interfere with the phonological loop (Papagno, Valentine, & Baddeley, 1991). Such learning, involving the modification and development of existing phonological representations, appears to be crucial in natural language acquisition, suggesting an important role for the phonological loop (see Baddeley, Gathercole, & Papagno, 1998).

Therefore, any adequate model of human memory must be capable of explaining not only how long-term phonological representations serve to enhance immediate memory performance, but also how new phonological structures may be created on the basis of the long-term phonological knowledge. In our view, a model in which working memory is merely the activation of LTM representations cannot adequately support the learning of new phonological structures, hence failing on the first criterion.

Consider the phonological processing stages of the pandemonium model outlined above. Let us assume, first of all, that this model adapts to a long-term "diet" of heard speech by developing representations that are characteristic of the language experienced, resulting in the capacity to detect readily the characteristic phonemes of that language. Furthermore, at a somewhat higher level within the same system, frequent clusters of phonemes also set up networks that optimize the detection of syllables and, at an even higher level within the hierarchy, words. Such a system would have the advantage of being well attuned to detecting the common linguistic entities of the language, but would have the disadvantage of being likely to fail to respond accurately to unfamiliar sound sequences because it would try to interpret the new sound in terms of its existing structure. Thus, new items might be "misheard" as familiar items, something that would make it difficult to add new words, or indeed the names of new people, to the existing system.

One way around this problem would be to have a *second* system that is much less influenced by past experience, but is capable of interacting with and gradually modifying the more durable long-term phonological system. This idea has a good deal in common with the proposal made by Hinton and Plaut (1987) about the utility of neural network systems with both slow and fast weights. The slow weights provide a durable long-term basis, while the fast weights provide a rapid and flexible learning system that is linked to the slow system but not dominated by it. The slow and fast weight systems might in principle either operate within the same structure or represent separate but strongly communicating structures (for a similar proposal, see Schneider, Chapter 10, this volume). Regardless of their precise realization, however, we propose that the slow and fast components may be considered functionally separate systems corresponding to long-term learning and temporary maintenance.

A second argument in favor of separate systems is that if the phonological loop is simply the activation of part of the speech system, then patients with a major STM deficit should have major speech-perception problems. Though it is often the case that patients with STM deficits will have some language problems, the classic cases on which the literature rests typically have either minimal and subtle language deficits (Shallice & Warrington, 1970), or, as in the case of PV (Vallar & Baddeley, 1984), no apparent deficit. It is also the case that patients with major language-processing deficits may nevertheless have a far better memory performance than the classic STM case (Baddeley & Wilson, 1993).

Hence, although we believe that the phonological loop uses much of the same system as is involved in speech perception and production, we would maintain that it represents a supplementary system that is specialized for the temporary maintenance of sound-based information (Baddeley et al., 1998). We accept that this system is influenced by existing phonological knowledge, but suggest that it must be sufficiently independent of that knowledge so that it can represent novel experiences with minimal distortion.

The Visual Cache and the Inner Scribe

Turning to the visuospatial sketchpad, we can formulate an analogous argument. As the phonological loop has been linked with, but seen as distinct from, the speech system, so the visual and spatial components of working memory have been linked with the visual imagery system and with the representation and planning of movement. As discussed earlier in this chapter, some of the relevant evidence comes from studies where subjects are required to retain a sequence of movements to targets (Logie & Marchetti, 1991), body movements generated by the experimenter (Smyth & Pendleton, 1989), or an imaged matrix (Baddeley & Lieberman, 1980; Logie et al., 1990). Recall performance on such tasks is impaired by asking subjects concurrently to tap a series of keys laid out on a table or to move their arm to follow a moving target. A number of studies also provide evidence that visual imagery and the processing and retention of visually presented information share cognitive resources (Logie, 1986: Logie et al., 1990; Quinn & McConnell, 1996).

Although the precise relationship between visuospatial working memory and visual imagery is still a matter of debate (Cornoldi, Logie, Brandimonte, Kaufmann, & Reisberg, 1996; Logie, 1995; Reisberg & Logie, 1993), the visual and spatial components of working memory do not seem to be synonymous with the imagery system. First, there is a case report of a patient who shows a clear dissociation between visuospatial working memory and mental imagery (Morton & Morris, 1995). More specifically, this patient (MG) performed poorly on typical mental imagery tasks involving mental transformation (e.g., mental rotation, mental scanning), whereas her performance on the temporary maintenance of visual and spatial information in working memory was essentially intact. This dissociation suggests that the visuospatial working memory system and the imagery system are not identical. Second, concurrent spatial tapping or arm movement, which is considered to disrupt the functioning of the visuospatial sketchpad, may or may not disrupt the performance of mental imagery tasks, depending on the nature of the imagery task (Pearson, Logie, & Green, 1996; Salway & Logie, 1995). Specifically, the necessity of temporary visuospatial storage of the image seems to be an important factor, again suggesting that imagery and temporary visuospatial storage are not synonymous.

Regardless of the nature of the relationship, it is generally agreed that both imagery and visuospatial temporary memory tasks involve activated long-term stored knowledge, coupled with information extracted from the sensory properties of the stimulus array. However, there is a body of evidence that points to visual and spatial working memory being identifiable, functionally separate cognitive functions, rather than reflecting the sum total of currently activated components of long-term knowledge. One of us (Logie, 1995) has argued that the visual and spatial knowledge that is activated has privileged access to, respectively, the visual (the visual cache) and spatial (the inner scribe) components of working memory, but that these systems are functionally separate. A schematic diagram of this view of visuospatial working memory is shown in Figure 2.2.

Other researchers have argued that images are interpreted within a particular frame of reference (Chambers & Reisberg, 1985, 1992), although there remains a debate as to the ease with which images can be reinterpreted without external stimulus support such as a picture (Brandimonte & Gerbino, 1993; Cornoldi et al., 1996). The idea is that the physical picture is divorced from the interpretation placed on the mental representation of the depicted material. Therefore, looking at an ambiguous picture on different occasions

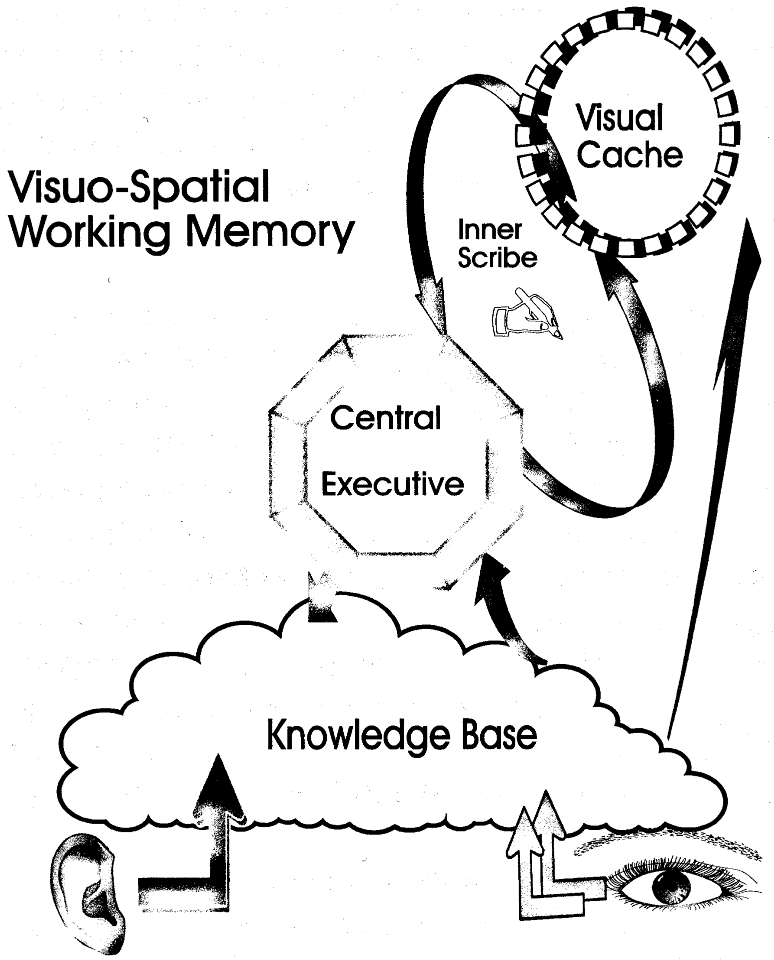

Figure 2.2. A schematic diagram of visuospatial working memory (derived from Logie, 1995).

allows for different interpretations to be formed on each occasion, and the reinterpretation of the mental image is facilitated by physical stimulus support (Chambers & Reisberg, 1985, 1992; Pearson et al., 1996). Reexamining the mental image without such stimulus support present simply reinforces the previous interpretation derived from the frame of reference for the image. Therefore, to be able to reinterpret the stored mental image, some sort of covert stimulus support is necessary, and we believe that the visual cache and the inner scribe may provide such support, enabling rehearsal and allowing novel interpretations to be applied to the current image (Cornoldi et al., 1996; Reisberg & Logie, 1993). In the context of the present chapter, the conclusion is that activated stored knowledge is transferred to the visuospatial components and the central executive of working memory. This information is then incorporated within the generated and manipulated representations supported by working memory components.

Data from patients with hemispatial neglect present complementary evidence for the functional separation of temporary maintenance of visuospatial information and stored imaginal knowledge. These patients appear to ignore half of their visual field, of objects and of their body space, most commonly on the left (for a review, see Bisiach, 1993). Interestingly, a number of neglect patients have recently been reported as having an additional difficulty with reporting from memory details of the imaged left half of familiar scenes such as buildings in a town square or the interior of their home (e.g., Bisiach & Luzzatti, 1978). It is even the case that a small number of patients appear to have difficulty with reporting details from memory, but not from perception (Guariglia, Padovani, Pantano, & Pizzamiglio, 1993; Beschin, Cocchini, Della Sala, & Logie, 1997). These patients can readily describe a scene with their eyes open, but omit details on the left when asked to describe that same scene after they close their eyes or to describe a familiar town square from a particular vantage point. However, these patients do not appear to have lost their memory of the square, because when asked to describe it from the opposite vantage point, they report details that are now on the imagined right and that were omitted. Such evidence points to a clear separation between the stored knowledge base, which appears to be intact, and the mental representation and manipulation of visual and spatial information in working memory.

Summary

In this section, we argued that LTM and working memory are closely related and that both systems may play a role in complex verbal and visuospatial tasks. However, we also argued that working memory cannot merely be an activated portion of LTM, because the two systems must serve different functions under certain situations (e.g., learning novel phonological information or reinterpreting visual images). Data from brain-damaged patients (with STM deficits and hemispatial neglect) provide further evidence that LTM and working memory must be functionally separate systems.

The Relationship of Working Memory to Attention and Consciousness

Although we would certainly not wish to identify working memory with attention, we do believe that the two concepts are closely related. The central executive is typically regarded as an attentional system (e.g., Cowan, Chapter 3; Engle et al., Chapter 4, this volume), and one might well use the general term *attention* to refer to the control processes that operate throughout the working memory system. Indeed, as one of us has previously suggested (Baddeley, 1993a), the use of the term *working memory*, rather than *working attention*, reflects the fact that we initially approached the system through its mnemonic capacities rather than its control mechanisms. Had we approached the same system from an attentional viewpoint, it would have been equally appropriate to label it "working attention."

It is important to point out, however, that the concept of attention itself is not unitary. Posner (1995), for example, distinguishes three separate attentional systems concerned respectively with orienting, alertness, and high-level attention, each represented by a separate anatomical substrate. It is clear that the control processes involved in the central executive are also complex and are likely to have substantial overlap with aspects of the more established approaches to the study of attention. Our own work has been strongly influenced by the attentional literature, particularly by the work of Norman and Shallice (1986), which contributed to our initial formulation of the central executive. Our more recent approaches, however, are beginning to reflect some of the work stemming from Posner's framework (e.g., Duncan, 1995; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994). As Engle et al. (Chapter 4, this volume) argue, we also expect the study of attention and of control processes in working memory to continue to interact productively.

As for the relationship between working memory and consciousness, one of us (Baddeley, 1993b) has argued that conscious awareness is a means of maintaining and coordinating information from a number of sources, including the present, specific episodes from the past, and projections as to the future and that working memory mediates this dynamic coordination. More specifically, working memory allows the organism to reflect on the available options and choose a particular action or strategy, rather than being driven by the sheer weight of past experience (for more detailed discussions, see Baddeley, 1993b, 1997). Although this view is highly speculative, it provides a way to empirically examine how working memory is related to conscious awareness. In a recent dual-task study, for example, Teasdale et al. (1995) demonstrated that the production of stimulus-independent thoughts – streams of thoughts and images unrelated to immediate sensory input – depends on the central executive. Another study also suggests that working memory might be related to the phenomenological experience of the vividness of visual imagery (Andrade, Kavanagh, & Baddeley, 1997; Baddeley & Andrade, 1998). Although more detailed exploration is certainly necessary, our model provides a useful framework to study consciousness and its relation to working memory.

The Biological Implementation of Working Memory

As will be clear from our discussion thus far, the development of our model of working memory has relied in part on detailed studies of brain-damaged patients. These studies have offered significant insight into the possible aspects of brain organization that might be linked to the operation of the various components of working memory. We have referred throughout the chapter to the studies of brain-damaged patients. There have in addition been a number of recent studies that have explored the use of neuroimaging techniques in normal subjects as they undertake working memory tasks.

The Phonological Loop

In the case of the phonological loop, Della Sala and Logie (1993) summarize the lesion sites for a number of patients with verbal short-term memory deficits who have been described by various researchers in the published literature. In 17 out of the 18 patients listed, the lesion was in the left hemisphere, with the 18th patient having more diffuse brain damage. For those patients, the lesions were primarily in the lower part of the parietal lobe close to the junction with the upper part of the posterior temporal lobe. This same general area has been confirmed as the locus of the lesion in group studies of patients with poor digit span (e.g., Warrington, James, & Maciejewski, 1986). More sophisticated localization techniques have identified the supra-marginal gyrus as the area most commonly damaged in cases of verbal STM impairment (e.g., Warrington, Logue, & Pratt, 1971).

It is of course possible that evidence linking impairment with areas in a damaged brain does not necessarily reflect the areas that support the same cognitive functions in the healthy brain. This particular issue is addressed neatly by more recent studies that have adopted measures of activity in the brains of healthy subjects. A number of studies have used positron emission tomography (PET) during the performance of various working memory tasks (Paulesu, Frith, & Frackowiak, 1993; Salmon et al., 1996). The data are broadly consistent in showing activity in the lower left supra-marginal gyrus during short-term verbal memory tasks, giving evidence that converges with the finding from brain-damaged patients.

The Visuospatial Sketchpad

The neuropsychological data corpus for visuospatial sketchpad is not as well endowed as its verbal counterpart. At a gross level, it appears that right hemisphere lesions are more commonly associated with visuospatial memory deficits (e.g., De Renzi & Nichelli, 1975). As to more specific anatomical localizations, there seems to be no clear consensus (see Della Sala & Logie, 1993, for more details). Note that there appears to be a clear distinction between the lesion sites associated with visuospatial working memory deficits and those linked with visual imagery deficits. In the latter case, some of the brain-damaged data seem to point to areas in the left hemisphere (Farah, 1984), while evidence from studies of representational neglect (e.g., Bisiach & Luzzatti, 1978; Beschin et al., 1997) and studies of lesions in monkeys (see Stein, 1992, for a review) link impairments in visuospatial representation with damage to the right posterior, parietal cortex.

PET studies of the normal brain have also implicated activity in the right hemisphere with visuospatial working memory tasks, although which areas are active within that hemisphere seems to depend on the nature of the task. Jonides et al. (1993) and Mellet, Tzourino, Denis, and Mazoyer (1995) reported activity in the occipital and parietal areas along with some activity in the prefrontal cortex and premotor areas during visuospatial imagery tasks. Kosslyn et al. (1993) have reported additional activity in the primary visual areas of the occipital lobe. However, Mellet et al. (1995) noted that the primary visual areas were involved only when their imagery task also involved some visual perceptual input. Courtney, Ungerleider, Keil, and Haxby (1996) have further reported that tasks involving visual working memory appear to generate activity in a range of areas excluding the right parietal lobe, whereas a spatial working memory task was associated with activity in the superior and inferior parietal cortex. They conclude that visual and spatial working memory are handled by different areas of the cortex, a finding consistent with our suggestion that these two functions of working memory are relatively independent (Logie, 1995).

The Central Executive

As one of us (Baddeley, 1986) argued earlier, executive or supervisory processes associated with the central executive seem to be closely linked to the prefrontal cortex, although it may not be the only brain area that supports the executive control of behavior. One particularly illuminating recent finding on the role of the prefrontal cortex in executive function is that performing a language task (i.e., semantic judgment) and a visuospatial task (i.e., mental rotation) simultaneously may require the contribution of the additional area of the brain – the prefrontal cortex – that is not necessarily implicated in the performance of individual component tasks (D'Esposito et al., 1995). The study has also shown that this intriguing finding is not merely a simple artefact of task difficulty or effort. Although more research is necessary, this result provides an initial promising step toward examining the neural basis of specific executive processes. A more detailed review of the role of prefrontal cortex in executive or supervisory processes are presented in Della Sala and Logie (in press) and also in the Engle et al. (Chapter 4, this volume) chapter.

Summary

Clearly the biological correlates of the various subcomponents in working memory remain to be fully explored. The data from neuroimaging studies and from brain-damaged patients, however, converge with the behavioral data in healthy subjects in supporting a multiple-component model (see Smith & Jonides, 1997, for a more detailed review of neuroimaging evidence supporting the multiple-component model of working memory).

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