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THE MULTI-COMPONENT MODEL OF WORKING MEMORY: EXPLORATIONS IN EXPERIMENTAL COGNITIVE PSYCHOLOGY

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Abstract—There are a number of ways one can hope to describe and explain cognitive abilities, each of them contributing a unique and valuable perspective. Cognitive psychology tries to develop and test functional accounts of cognitive systems that explain the capacities and properties of cognitive abilities as revealed by empirical data gathered by a range of behavioral experimental paradigms. Much of the research in the cognitive psychology of working memory has been strongly influenced by the multi-component model of working memory [Baddeley AD, Hitch GJ (1974) Working memory. In: Recent advances in learning and motivation, Vol. 8 (Bower GA, ed), pp 47–90. New York: Academic Press; Baddeley AD (1986) Working memory. Oxford, UK: Clarendon Press; Baddeley A. Working memory: Thought and action. Oxford: Oxford University Press, in press]. By expanding the notion of a passive short-term memory to an active system that provides the basis for complex cognitive abilities, the model has opened up numerous questions and new lines of research. In this paper we present the current revision of the multi-component model that encompasses a central executive, two unimodal storage systems: a phonological loop and a visuospatial sketchpad, and a further component, a multimodal store capable of integrating information into unitary episodic representations, termed episodic buffer. We review recent empirical data within experimental cognitive psychology that has shaped the development of the multicomponent model and the understanding of the capacities and properties of working memory. Research based largely on dual-task experimental designs and on neuropsychological evidence has yielded valuable information about the fractionation of working memory into independent stores and processes, the nature of representations in individual stores, the mechanisms of their maintenance and manipulation, the way the components of working memory relate to each other, and the role they play in other cognitive abilities. With many questions still open and new issues emerging, we believe that the multicomponent model will continue to stimulate research while providing a comprehensive functional description of working memory. © 2006 Published by Elsevier Ltd on behalf of IBRO.

Key words: dual task, central executive, phonological loop, visuospatial sketchpad, episodic buffer.

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Abbreviations: AD, Alzheimer's disease; DVN, dynamic visual noise; fMRI, functional magnetic resonance imaging; PET, positron emission tomography; SAS, supervisory activating system.

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Many disciplines within cognitive neuroscience have individually and in synergy substantially contributed to the gathering of empirical results and the development of theoretical models that constitute our understanding of working memory. The aim of this review is to present insights that have been enabled by experimental behavioral studies within cognitive psychology. Specifically, we will focus on recent empirical findings that relate to the multi-component model of working memory, a functional model of working memory developed by Baddeley and Hitch (1974; Baddeley, 1986, 2000) that has introduced the concept and inspired decades of research into the capacities, properties and mechanisms of working memory.

The subject of working memory, like any other within cognitive neuroscience, can be and is approached from many different levels of description (see Repovš and Bresjanac, 2006). Each level of description is a valid one and contributes importantly to a complete understanding of the phenomenon under investigation. While neuroscience provides a glimpse into the structural underpinnings of the cognitive system and computational cognitive neuroscience addresses the question of how the information processing is actually carried out, the role of cognitive psychology is to provide a detailed description of the properties and the capacities of the system, to map out a model of its functional components and the way they relate to each other.

A promise of novel insights and important advancements in understanding working memory provides a strong incentive to combine the findings of different disciplines and levels of description. In doing so, however, one has to be wary of a seductive mistake, namely to equate or conflate the functional and structural levels of description or to assume a one-to-one mapping between them. Many cognitive functions and processes are carried out by a network of brain regions, and individual regions can take part in the execution of a number of functional components of the system. The exact relation between them is often far from straightforward. To be able to avoid mistakes one has to be able to distinguish the levels clearly and be conscious of, and specific about, the mappings proposed. To facilitate that, we will purposefully limit this review to a functional account of working memory as explored and revealed thorough behavioral experimental studies. Our goal is to describe the behavioral properties and capacities of working memory and to outline a model that hopes to explain them. We are not of course pretending that this is the whole story. Indeed, many features of the presented model were inspired or tested by neuropsychological findings.

While we refrain from citing and discussing findings from other disciplines in the main body of the paper, we wholeheartedly support the ultimate goal of relating and combining levels of description in a comprehensive multidisciplinary model of working memory. Some possible complementary lines of research and findings will be presented in the last part of the paper, while more complete accounts of such integration are given in other papers presented in this special issue.

The outline of the paper follows the structure of the Baddeley and Hitch (1974; Baddeley, 1986, 2000) multicomponent model of working memory. First, we will present a short introduction and a sketch of the model. We will follow this by focusing on each individual proposed component of working memory, reviewing recent empirical findings that have expanded our empirical knowledge and influenced the further development of the theoretical model. For a more detailed analysis of the development of the model and related empirical findings, please refer to Baddeley and Hitch (1974) and Baddeley (1986, 2000, in press). Readers interested in alternative models of working memory are encouraged to consult Miyake and Shah (1999) as well as other papers in this special issue.

The multi-component model of working memory

There are a number of ways in which the temporary storage of information can be realized within a cognitive system. One can for instance envision a distributed system with a set of independent processors that communicate with each other. Baddeley and Hitch (1974) instead argued for the concept of a common system that is "limited in capacity and operates across a range of tasks involving different processing codes and different input modalities" (Baddeley, 1986, p. 35). To support their claim, they devised and carried out a set of experiments designed to test a single, but important hypothesis. Namely, if a common system of limited capacity is employed in a range of cognitive tasks, then absorbing a substantial amount of its capacity by a concurrent supplementary task should have deleterious effects on performing those tasks, even when they do not have an obvious short-term memory component.

In a range of experiments, the simple concurrent task of holding and speaking out loud a sequence of six digits proved to have important effects on learning, comprehension and reasoning (for a thorough overview see Baddeley and Hitch, 1974, and Baddeley, 1986). The results provided both a persuasive argument in support of the general concept of a working memory system as well as information that led to the formulation of a specific multi-component model of working memory (Baddeley and Hitch, 1974). The reported results and the method developed have led to a wealth of empirical research that has enabled further testing and development of the model.

The initial model presented by Baddeley and Hitch (1974) proposed the existence of three functional components of working memory (Fig. 1). A *central executive* was envisioned as a control system of limited attentional capacity that is responsible for the manipulation of information within working memory and for controlling two subsidiary storage systems: a *phonological loop* and a *visuospatial sketchpad*. The phonological loop was assumed to be

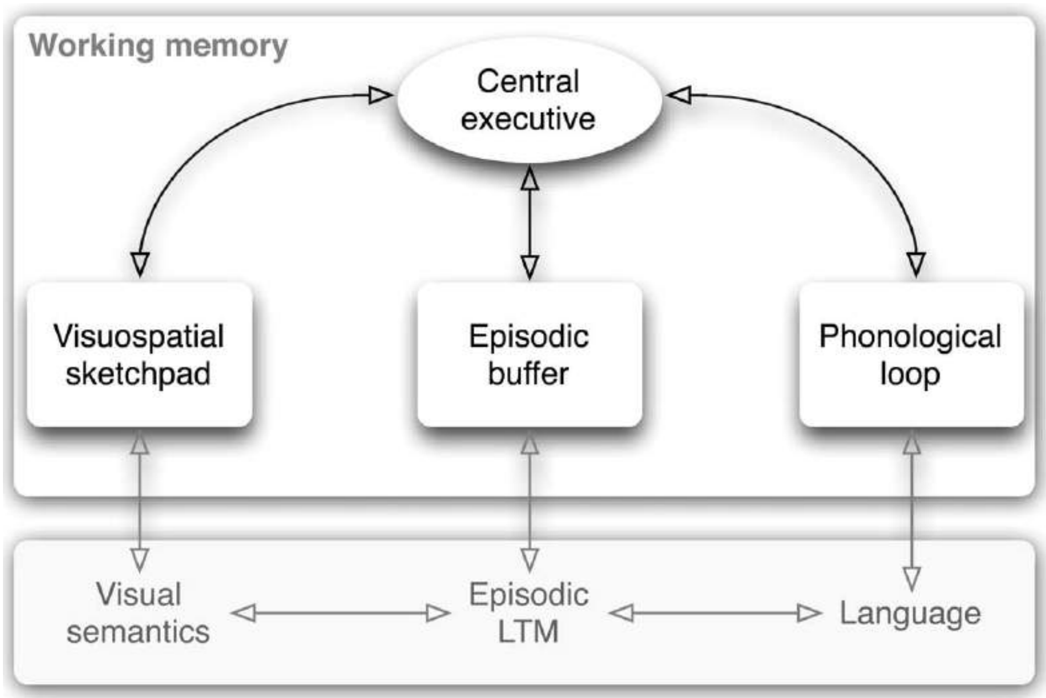

Fig. 1. The current multi-component model of working memory representing "fluid" capacities (such as attention and temporary storage) that do not change by learning and their proposed relations to "crystallized" cognitive systems capable of accumulating long-term knowledge.

responsible for the storage and maintenance of information in a phonological form, while the visuospatial sketchpad was dedicated to the storage and maintenance of visual and spatial information. Based on a number of empirical findings a fourth component, the *episodic buffer*, was added recently (Baddeley, 2000). The episodic buffer is assumed to be a limited capacity store that is capable of multi-dimensional coding, and that allows the binding of information to create integrated episodes. The paper will address each of the proposed components in turn, first presenting the theoretical model and then reviewing the relevant empirical findings.

The phonological loop

The phonological loop comprises two components, a phonological store, which holds memory traces in acoustic or phonological form that fade in a few seconds, and an articulatory rehearsal process analogous to subvocal speech (Baddeley, 1983). The function of the articulatory rehearsal process is to retrieve and re-articulate the contents held in this phonological store and in this way to refresh the memory trace. Further, while speech input enters the phonological store automatically, information from other modalities enters the phonological store only through recoding into phonological form, a process performed by articulatory rehearsal. As the articulation operates in real time, the capacity of the phonological store is limited by the number of items that can be articulated in the time available before their memory trace has faded away. A number of important empirical findings support the assumptions of the model.

Limited span. The most basic finding related to the verbal short-term store is the limited amount of information it can hold. Measured by a simple task of immediate serial recall, it can hold from about five to eight items (Brener, 1940). However, as many experiments show, the number of items held, depends on their characteristics. These findings further reveal the structure of the verbal short-term store.

The phonological similarity effect. Research predating the model (e.g. Conrad, 1964; Conrad and Hull, 1964) had already shown that sequences of dissimilar sounding letters such as W, X, K, R, Y and Q are easier to remember than sequences of similar sounding letters, such as V, B, G, T, P and C. This finding has been replicated many times and research has shown that while similarity of sound affects the number of words recalled, similarity of meaning has little effect (Baddeley, 1966a). As the degree of phonological similarity within the sequence crucially determines the number of items recalled, the items are most probably stored in a phonological code. In contrast, the long-term learning of such material is influenced by similarity of meaning, but not of sound (Baddeley, 1966b).

The irrelevant sound effect. Exposure to irrelevant speech either concurrent or subsequent to presentation of list items significantly reduces serial recall of verbal material. First reported by Colle and Welsh (1976) with visually presented items, the effect was demonstrated both with visually presented stimuli (e.g. Ellermeier and Zimmer, 1997; Jones, 1994; Jones and Macken, 1995; Jones et al., 1992; Salamé and Baddeley, 1982; Surprenant et al., 2000) as well as with auditorily presented items (e.g. Hanley and Broadbent, 1987; Neath et al., 1998). Further research has shown that the effect is not limited to speech and music, but appears with other forms of fluctuation in the state of the irrelevant stimulus stream such as variable tones (Jones, 1993; Jones et al., 1996). Furthermore the effect of irrelevant speech is equal for phonologically similar and dissimilar remembered items (Salamé and Baddeley, 1986) and is also unaffected by phonological similarity between the irrelevant speech and the material to-be-remembered (Jones and Macken, 1995; Larsen et al., 2000; LeCompte and Shaibe, 1997), which speaks against an account in terms of the phonological masking of the memory trace.

A number of theoretical accounts were proposed for the explanation of the irrelevant speech effect, based on temporal distinctiveness theory (TDT, LeCompte, 1996), the feature model (Nairne, 1990; Neath, 2000), and the object-oriented episodic record (O-OER) model (Jones, 1993). However, additional research has shown that the irrelevant sound effect is a) additive to the phonological similarity effect (Hanley and Bakopoulou, 2003), b) absent when the to-be-remembered items are not encoded into the phonological store (Norris et al., 2004), c) present even if irrelevant sounds are presented only during a post-presentation retention interval, and at that d) even when subvocal rehearsal is prevented (Hanley and Bakopoulou, 2003, Norris et al., 2004). These findings can not be readily explained by the alternative models. The fact that the irrelevant sound effect seems to be brought about by interfering with the representation while it is being held within the phonological store is, however, consistent with the phonological loop account. The exact mechanism of irrelevant speech effect is still uncertain, but the evidence suggests an effect based on the representation of serial order within the phonological store (Norris et al., 2004). A candidate account is provided by the Page and Norris (2003) primacy model which suggests that the irrelevant sound effect comes about through a competition for resources between the representation of list order in the to-be-remembered list and the competing cue order within the irrelevant sounds list. This interpretation has some similarity with that proposed by Jones (1993), but is contained within a computationally explicit model of the phonological loop.

The word length effect. Immediate memory for word sequences declines as the spoken length of words increases (Baddeley et al., 1975). This robust finding was initially interpreted as reflecting the decay of a memory trace over time, with long words taking longer to rehearse hence allowing more decay than short. Alternative interpretations have been proposed in terms of word complexity (Caplan et al., 1992; Service, 1998, 2000). In an attempt to rule out this interpretation, a number of studies have compared the retention of disyllabic words comprising either rapidly spoken short vowel sounds (e.g. *bishop*, *wicket*) or long (e.g. *harpoon*, *Friday*). An effect of duration was found by Baddeley et al. (1975), but not by others using different items (Lovatt et al., 2000, 2002; Caplan and Waters, 1994). A recent study by Mueller et al. (2003) took special care to assess the extent of phonological similarity among words and their articulatory duration, concluding that "phonological complexity per se may have no reliable effects on memory spans over and above those attributable to mean articulatory durations and phonological dissimilarity" (p. 1363). We suspect, however, that the controversy will continue.

Articulatory suppression. When participants are instructed to repeatedly articulate an unrelated word, the function of the articulatory rehearsal process is disabled, leading to a number of consequences that provide additional tests of the model. First, in the presence of such articulatory suppression, the word length effect is abolished (Baddeley et al., 1984), which further supports the model's assumption that subvocal articulation in real time serves to refresh the decaying memory traces within the phonological store. The ability to remember items, though significantly impaired, is however not nonexistent, which suggests that there are other possible ways of storing verbal information, one candidate being the episodic buffer.

Second, articulatory suppression during visual presentation of items to be remembered disables the transfer of information to phonological store as evidenced by the removal of the effects in that condition of either phonological similarity (e.g. Baddeley et al., 1984; Longoni et al., 1993; Murray, 1967, 1968) or irrelevant sound (Salamé and Baddeley, 1982; Hanley, 1997). The presence of the effects of irrelevant speech (Hanley and Broadbent, 1987; Hanley and Bakopoulou, 2003) and of a phonological similarity effect (Murray, 1968) despite articulatory suppression in the case of auditory presentation of list items on the other hand implies that speech indeed has automatic and privileged access to the phonological store, bypassing the articulatory rehearsal process.

Conclusion. The phonological loop was the first and the most studied component of the multicomponent model of working memory. The initial assumptions of the model seem to have withstood the vigorous onslaught of empirical testing and proved the model to be robust and well capable of explaining phenomena related to verbal working memory. We can expect further research to provide novel challenges to the model and help map the detailed mechanisms employed in the maintenance of phonological information in serial order.

The visuospatial sketchpad

While the phonological loop is specialized to hold verbal information, the visuospatial sketchpad is assumed to be capable of maintaining and manipulating visual and spatial information, a process that is crucial for performing a range of cognitive tasks. While initially, most working memory research focused on verbal material and therefore the phonological loop, recently a number of studies have provided a wealth of interesting results relating to the functional structure and properties of visuospatial working memory. In the following sections we will address recent findings related to the fractionation of the visuospatial sketchpad and then focus on the form of representation and mechanisms of maintenance in its visual and spatial subcomponents respectively. We will conclude the section with an integration of the current ideas and findings related to the visuospatial sketchpad.

Fractionation of visuospatial working memory. From a functional point of view, a range of experiments has provided evidence for both domain and process divisions within visuospatial working memory. Encouraged by a number of experimental findings (Baddeley, 1996; Logie, 1986; Logie et al., 1990) and neuropsychological findings (Baddeley et al., 1991b; De Renzi and Nichelli, 1975; Shallice and Warrington, 1970), Della Sala et al. (1999) have shown that a spatial interference task significantly disrupts performance on the Corsi block tapping test of spatial working memory, while it has no effect on the visual patterns test, a test of visual working memory, while a visual interference task has the opposite effect. The results therefore provided clear evidence for the existence of separate visual and spatial subcomponents of non-verbal working memory.

To account for possible alternative explanations of the results obtained by Della Sala et al. (1999) as well as other studies investigating the visual–spatial division of working memory (e.g. Hartley et al., 2001), Klauer and Zhao (2004) designed and performed a number of experiments that further explored the distinction between the two subsystems and provided a persuasive set of double dissociations between the two proposed subsystems. The results not only supported the existence of separate visual and spatial stores, but also provided evidence for separate rehearsal mechanisms for visual and spatial information, independent of the central executive. The latter results agree with the study performed by Bruyer and Scailquin (1998), which has shown that only manipulation and not maintenance shares resources with the central executive.

Additionally, research into the role of working memory in visual search has shown that visual and spatial working memory tasks differentially interact with visual search (Oh and Kim, 2004; Woodman et al., 2001; Woodman and Luck, 2004). In a dual-task condition, a concurrent visual working memory task did not affect the efficiency of visual search as demonstrated by lack of change in the search rate, nor was its accuracy affected by visual search (Woodman et al., 2001; Oh and Kim, 2004). Spatial working memory tasks on the other hand reduce the efficiency of visual search as shown by an increase in the slope of the function relating reaction time to the number of items in the search array, while the accuracy of the working memory task was reduced as well (Oh and Kim, 2004; Woodman and Luck, 2004).

While the research described has provided strong evidence for separate visual and spatial storage and maintenance components of working memory, Mohr and Linden (2005) suggest that passive and active processes in visual working memory should be distinguished as well. Passive processes are recruited by tasks that require recall of information in the same format as it was memorized, while active processes are recruited by tasks that require the information to be modified, transformed, integrated or otherwise manipulated. In a series of experiments, these authors have shown a lack of interference between concurrent color and spatial manipulation tasks in comparison to a single task condition, whereas interference was present in dual task conditions within the same domain. Additionally and in accordance with previous results (Bruyer and Scailquin, 1998), the manipulation tasks in both domains interfered with a concurrent random generation task that is assumed to rely heavily on the central executive, while interference was absent in the case of maintenance tasks. The results provide evidence of independent resources for manipulation within the visual and spatial components of working memory with both sharing resources with the central executive.

Taken together these studies show that visuospatial working memory is not a unitary system, but can be further divided into spatial and visual subsystems each with its independent storage, maintenance and manipulation processes. Of these, maintenance seems to be independent of executive processes while manipulation depends on them.

A formal fractionation of the visuospatial sketchpad analogous to the phonological loop was proposed by Logie (1995). Logie (1995) proposes a distinction between a passive visual storage component, termed the visual cache, and a dynamic spatial retrieval and rehearsal process, termed the inner scribe. While the proposal provides a good account of the neuropsychological data (e.g. Della Sala and Logie, 2002), the model does not allow for separate maintenance mechanisms for the contents of visual and spatial stores as suggested by the reviewed empirical data.

Representation and maintenance of information in visual working memory. A number of varied studies bear on the question of representation within visuospatial working memory. Having established the existence of separate stores for visual and spatial information, we can assume that the representations used differ as well. In a series of experiments aimed at measuring the capacity of visual working memory Luck and Vogel (1997) and Vogel et al. (2001) established that observers are able to retain information about three to four different features within a single dimension (e.g. color, orientation) but that these can be further combined with an additional three to four features from another dimension when integrated into objects. In this fashion, observers were able to retain 16 individual features when distributed across four objects, each defined by a conjunction of four features. Based on the finding that visual working memory is constrained by the number of objects and not by the number of distinguishable features that make up those object, the authors concluded that information in visual working memory is retained in the form of integrated objects.

Relating to the feature integration theory (Treisman, 1993), Wheeler and Treisman (2002) pointed out that the results of Luck and Vogel (1997) and Vogel et al. (2001) could also be explained by assuming parallel feature-specific memory stores of independent capacity. If capacity is limited only within a specific feature store, then the number of distinct features retained can be doubled, tripled or even quadrupled when features differ over independent dimensions, without the need for the information to be bound into integrated objects. To explore the alternative explanation Wheeler and Treisman (2002) specifically tested whether only the features are retained, or the specific conjunctions are retained as well. Across a number of change detection experiments, the authors showed that the features are maintained independently of their binding, which the participants often failed to retain. While the retention of specific features was rather robust, the retention of binding was vulnerable and seemed to depend on the participants' limited attentional resources. It is worth noting at this point that Wheeler and Treisman (2002) tested performance using an array of items, which required the subjects to scan before responding, whereas Luck and Vogel (1997) typically probe with a single item. Subsequent work by Allen et al. (in press) suggests that the binding together of features may require little in the way of additional attention, but that such bindings may be more readily disrupted by the processing of subsequent items.

Further insight relating to the form of representations retained in visual working memory was provided by Alvarez and Cavanagh (2004), who tested the capacity of working memory for objects of varying complexity. Their results revealed a strong linear relation between search rate and the number of objects retained and showed that "the upper storage limit of four or five items is attainable only by the very simplest objects; as the visual information load per item increases, the storage limit drops to substantially lower levels" (p. 110). The results are congruent with the proposal by Wheeler and Treisman (2002) that the number of objects retained depends on the maximum number of distinct features that can be retained within a specific dimension. For simple objects that consist only of single features within separate dimension (e.g. color, orientation) the number can be equal to the number of distinct features that can be retained within those dimensions, enabling four to five objects to be retained. Objects that themselves combine conjunctions of features within the same dimensions, quickly exhaust the available number of retained distinct features within a specific dimension, significantly limiting the total number of retained objects.

Another study by Barnes et al. (2001), made use of the single object advantage—a finding that two attributes can be more effectively discriminated when being part of a single object as compared with being a part of two different objects (Duncan, 1984; Baylis and Driver, 1992). In a dual task paradigm, Barnes et al. (2001) showed that only an object working memory task significantly reduced the single object advantage while verbal, and spatial working memory tasks had no effect. Based on these results the authors concluded that the same attentional mechanisms are engaged in maintaining objects in working memory and selecting perceptual objects in a visual scene.

Based on the empirical results gathered so far we can assume that the retention of integrated objects is accomplished by a binding mechanism depending on limited attentional resources. The exact form of representation and mechanisms of maintenance of individual features in visual working memory, on the other hand, is still unclear. Further insight might come from lines of research relating visual working memory to perception and visual imagery. At the same time more attention will have to be paid to the distinction between information held in visuospatial working memory and the episodic buffer, as some studies (e.g. Baddeley and Andrade, 2000; Zimmer et al., 2003) already suggest that episodic buffer might be involved in the representation and storage of integrated visual information.

Visual working memory, perception and experience. More than other components of working memory, visual working memory seems to be closely related to perception. The visual world itself, with its relatively stable and persistent character provides a form of external continuing memory record, which makes detailed visual retention somewhat redundant (O'Regan, 1992). Relying on a relatively limited capacity, visual working memory is geared toward effectively representing the most relevant features of the visual world. When perception of a scene is briefly interrupted, viewers often fail to detect quite major modifications in the scene, the phenomenon of *change blindness*. Based on this research, Rensink et al. (1997) suggested that the knowledge of the structure of visual scenes accumulated in long-term memory is used to detect the regions of central interest, which then guide attention and the transfer of information into visual working memory. The detection of any changes in the visual scene is therefore most likely to be limited to those regions of interest.

The top-down influences on the transfer of information to visual working memory were recently investigated in relation to the representation of objects. Wagar and Dixon (2005) explored how the relevance of specific features for category judgment, affects their encoding and maintenance in working memory. Their findings showed that in a change detection paradigm, a change in features that were important for categorization (diagnostic features) was significantly more likely to be detected than a change in non-diagnostic features. The results suggest that previous experience importantly affects the encoding of information into working memory.

However, the transfer of information to working memory is not only mediated by top-down perceptual experience, but also by bottom-up features of visual information such as visual cues (Schmidt et al., 2002), perceptual grouping (Woodman et al., 2003) and object-based feature binding (Xu, 2002). Schmidt et al. (2002) showed that their subjects were more accurate in a visual working memory task when the item to be later probed was preceded by a visual cue, even when the cue was not predictive of the location that was probed. The authors concluded that the cue automatically influences the transfer of visual information into working memory. Expanding on the findings by Schmidt et al. (2002), Woodman et al. (2003) explored whether bottom-up perceptual grouping cues, such as gestalt principles of proximity and connectedness, may bias the entry of items into visual working memory. In a change detection task the subjects were indeed more likely to detect a change in objects perceptually grouped with the cued object, than a change in ungrouped objects, leading to the conclusion that the perceptual organization of visual input influences its transfer into visual working memory. Finally, Xu (2002) showed in a change detection task, that the features of objects are best retained when they belong to the same part of an object, less well when they belong to a different part of an object and worst when they form spatially separated objects.

A direct link between visual working memory and perceptual input is provided by the irrelevant picture effect. A number of studies (e.g. Della Sala et al., 1999; Logie and Marchetti, 1991; Quinn and McConnell, 1996) have shown that the presentation of irrelevant pictures disrupts the maintenance of information in visual working memory (but not spatial working memory). Further studies by McConnell and Quinn (2000) showed that there has to be a dynamic aspect to the interfering display. In a subsequent study McConnell and Quinn (2004) showed that aspects of visual complexity such as the number of dots, their density and the overall size of the visual noise field determine the degree of interference by visual noise fields with visual working memory. Based on their results they concluded that the passive visual store is directly accessible by externally presented interference, bypassing higher-level knowledge-based analysis.

There have however been some problems in reliably replicating the interference effect based on the dynamic visual noise (DVN) paradigm developed by Quinn and McConnell (1996). Andrade et al. (2002) tested the interference effect of DVN on the recall of static matrix patterns, recognition of arrays of matrix patterns and recognition of Chinese characters, as well as on the peg-word mnemonic task used by Quinn and McConnell (1996; McConnell and Quinn, 2004). While the peg-word mnemonic task showed a robust effect of interference, none of the other tasks did. Similar findings were reported by Zimmer and Speiser (2002). Andrade et al. (2002) explained their results by differentiating between visual imagery, which in their opinion is employed in the peg-word mnemonic task, and visual short-term memory, which is probed by the other tasks used in their study. They conclude that the two types of task either load different components of working memory, or else that DVN disrupts only the processing included in visual imagery without disrupting the storage of the underlying representation. As the peg-word mnemonic task involves the creation of new visual images based on long-term memory, it is also possible, that it involves the episodic buffer rather than the visual subcomponent of visuospatial sketchpad. With conscious awareness providing the mechanism for retrieval from the episodic buffer (Baddeley, 2000), presentation of salient changes in the visual input presents a good candidate for interference with the contents of the buffer.

Representation and maintenance in spatial working memory. Building on an analogy with the separation of passive store and active rehearsal mechanism within the phonological loop, and a number of studies showing that voluntary eye movements disrupt spatial working memory, Baddeley (1986) initially proposed that covert eye movements, visiting the locations to be remembered, might serve as an active rehearsal mechanism. Noting that focus of attention moves with the eyes, Baddeley (1986; c.f., Postle et al., 2006) also suggested that the system that controls visual attention, and not the control of eye movements itself, might be crucial for the rehearsal of spatial information.

In addition to voluntary eye movements, studies have shown that other forms of concurrent body movement such as sequential tapping of keys (e.g. Logie and Marchetti, 1991; Pearson et al., 1999; Smyth et al., 1988; Smyth and Pendleton, 1989) and arm movements across an unseen matrix (Quinn, 1994; Quinn and Ralston, 1986) also produce interference with spatial working memory. Interference was additionally shown not to be dependent on actual performance of movement, but is present even when the participants are asked only to imagine making an arm movement (Johnson, 1982). It seems that the planning of movements and not the actual execution is the source of interference with spatial working memory. A possible explanation of the findings was proposed by Logie (1995) who assumed that the inner scribe component of visuospatial sketchpad, otherwise responsible for active rehearsal of information held within passive visuospatial cache, is also involved with extraction of information used for planning and execution of voluntary movements, causing the interference when both tasks have to be performed.

As already hinted by Baddeley (1986), both voluntary eye and arm movements are accompanied by shifts of spatial attention. Could it be that it is not the movement itself, but rather a more general process of shifting spatial attention, common both to the eye and arm movement, that is causing the interference observed? A study by Smyth and Scholey (1994) showed that attention is indeed involved in producing the interference, while a follow-up study by Smyth (1996) controlling for eye movements further ascertained that the shifts in spatial attention can by themselves produce interference with the spatial working memory span.

Building on results by Smyth (1996), Awh et al. (1998) showed that visual processing is facilitated at the locations maintained in spatial working memory compared with locations not maintained in spatial working memory. Additionally, in line with the results by Smyth (1996), they have shown that if subjects are forced to direct attention away from locations held in working memory their ability to remember those locations is impaired. Based on their empirical data, Awh and Jonides (2001) concluded that a functional overlap exists between the mechanisms of spatial working memory and spatial selective attention. In their opinion it is the mechanisms of spatial attention, such as focal shifts of attention to memorized locations that provide a rehearsal-like function of maintaining information active in spatial working memory.

A close relation between spatial working memory and attention was also revealed by studies of visual search. While the effectiveness of visual search as measured by search rate was shown to be unaffected by a concurrent verbal (Logan, 1978) or visual material load on working memory (Woodman et al., 2001; Oh and Kim, 2004), a spatial working memory task significantly slowed visual search and reduced its accuracy (Woodman and Luck, 2004; Oh and Kim, 2004). These results point to a common resource, employed by both visual search and maintenance of information in spatial working memory. The authors point to a number of possible candidates for a common resource. Both tasks could rely on the allocation of spatial attention, they could share a common system for representing spatial information, or spatial working memory could be actively involved in keeping track of already visited locations in visual search.

While attention has been shown to affect spatial working memory (Smyth, 1996; Awh et al., 1998), that does not by itself prove that it is only the shifting of attention that contributes to the interference of voluntary eye and limb movements with spatial working memory, an issue that was more directly addressed in recent studies. A study by Lawrence et al. (2001) examined the effect of saccadic eye movement, limb movement, and saccade inhibition on memory span for spatial locations. As all three tasks produced comparable interference with spatial span, the authors concluded that all spatial movements irrespective of the type produce similar effects on spatial working memory, congruent with a hypothesis of a common mechanism of interference, such as the shifting of spatial attention proposed by Awh and Jonides (2001). Later studies by Pearson and Sahraie (2003) and Lawrence et al. (2004) suggested rather different conclusions, both showing that eye movements resulted in an interference effect that was significantly stronger than shifts of attention alone. Pearson and Sahraie (2003) additionally showed that the greater interference in eye movement tasks was mostly due to mistakes in spatial and not temporal coding. The authors of both studies concluded that the interference associated with eye movements cannot be explained only in terms of shifts of attention. Lawrence et al. (2004) further suggest that changes in the retinal coordinates of the to-be-remembered locations, and the cognitive suppression of spatial processing during the execution of eye movement might be the causes of the additional interference effect observed, while Pearson and Sahraie (2003) propose that oculomotor control processes play a crucial role in short-term rehearsal of location-specific representations in working memory.

Further exploring the link between eye movements and spatial working memory, Theeuwes et al. (2005) conducted an experiment in which they observed eye movements directed either toward or away from the to-be-remembered location. Based on the strong link between visuospatial working memory, spatial attention and eye movements, and on previous findings that eye movements may deviate away from visible stimuli that need to be ignored (e.g. Doyle and Walker, 2001; Sheliga et al., 1994), the authors suggested that a remembered location might induce a similar deviation in eye movements away from the to-be-remembered location. These results supported the hypothesis of a strong link between visuospatial working memory and eye movements and gave support to the assumption that locations in spatial working memory might be represented also at the oculomotor level.

Conclusion. The empirical data reviewed have provided a wealth of information on the capacities and properties of the visuospatial working memory. The studies have not only confirmed the original assumption of the multicomponent model (Baddeley and Hitch, 1974) that visuospatial memory forms a distinct component of the working memory, but have also provided evidence for further fractionation. The empirical evidence suggests that visuospatial working memory can be further divided into visual and spatial subcomponents, each with separate and independent passive storage, representations, mechanisms of maintenance, and manipulation. Both subcomponents have been shown to be closely related to forms of visual attention.

Representation in the visual subsystem seems to be based on the relatively robust retention of a small number of distinct basic features (e.g. color, shape, orientation) that are independently stored in a set of parallel feature-specific stores. The retained individual features can then be bound together into integrated object representations and maintained through more vulnerable attentional mechanisms. The encoding of information in visual working memory has been shown to be significantly affected by both bottom up perceptual features, and by top down influences based on previous experience such as category learning.

While visual working memory is closely related to perception and visual imagery, spatial working memory shows closer connection to attention and action. The exact nature of the relation is not yet established, but the empirical findings suggest that spatial working memory shares important resources with spatial attention and oculomotor control.

The recent empirical findings seem to have overtaken the theoretical model. The extension of the original Baddeley and Hitch (1974) model proposed by Logie (1995) separating the visuospatial sketchpad in a manner that is analogous to the phonological loop, into a passive visual cache and a dynamic spatial inner scribe is not able to account for all the data. The theoretical model clearly needs to be further elaborated. Two possible and promising directions of development seem to be related on one hand to the feature integration model of visual attention (Treisman, 1993) and to a model of visual imagery (Kosslyn, 1994) on the other. An important future task for the multicomponent model is to distinguish clearly between representations held in the visuospatial sketchpad and those held in the episodic buffer. This is especially relevant in the case of visual imagery, which integrates visual information from various sources, including long-term memory, a task for which the episodic buffer would seem to be most suitable.

The central executive

The central executive has been the most important but least understood and least empirically studied component of the multi-component working memory model (Baddeley, 1986, 1996). Initially, it was conceived in rather vague terms as a limited capacity pool of general processing resources. As such, it functioned as a homunculus and served as a convenient ragbag for unanswered questions related to the control of working memory and its two slave subsystems. While such a homunculus cannot provide an acceptable explanation of the phenomena, it can serve a useful function by identifying the functions and properties that still need to be explained. They can then be systematically investigated until there is nothing left to explain and the homunculus effectively vanishes (Baddeley, 2001).

To sketch a functional model of the central executive, two general questions need to be answered. First, what is the role of the central executive in the functioning of working memory? Specifically, when and how does the central executive interact with the slave subsystems? Second, what other cognitive functions and abilities are dependent on the central executive? In recent years a number of studies have helped advance our understanding of the central executive, mapping out its role in the control of the slave subsystems, in the manipulation of information within working memory and in attentional control. In this section we will first present efforts to define the processes and capacities of the central executive. We will then move on to discuss the rather scarce findings relating to the role of central executive within the performance of working memory. Next, we will touch upon recent findings that explore the involvement of working memory in attentional processes employed in distractor interference tasks and in visual search. We will finish the section with some concluding thoughts.

Fractionating the functions of the central executive. The first attempt at replacing the homunculus (Baddeley, 1986) came with the adoption of the Norman and Shallice (1986) model of attentional control, which assumes two basic control processes. Most human action consists of routine tasks that can be controlled by schemata and habits employing environmental cues. Different cues frequently contradict each other, but most conflicts can be easily resolved using fairly automatic conflict-resolution processes. In the Norman and Shallice (1986) model these situations are resolved using a process they termed contention scheduling. Novel situations and problems however, cannot be resolved using automatic processes based on previous experience. In these cases a novel solution needs to be planned and followed through, based on the active combination of existing stimuli and information stored in long-term memory. In the Norman and Shallice (1986), model, this is assumed to depend on a limited capacity attentional component they termed the supervisory activating system (SAS).

Adopting the SAS as a model of the central executive did not dispel the homunculus, but it did provide a framework for specifying the processes and capacities needed by such an attentional controller. Four basic capacities were postulated and explored (Baddeley, 1996): the ability to focus, to divide and to switch attention, and the ability to relate the content of working memory to long-term memory. The capacity to focus attention was explored using a random digit generation task, which was argued to place a heavy load on the central executive (Baddeley et al., 1998). In a study by Robbins et al. (1996) it has been shown that while chess playing is not disrupted by articulatory suppression, it is significantly disrupted by a concurrent visuospatial task and even more so by a random digit generation task. The random digit task has also been shown to significantly disrupt category generation tasks (Baddeley, 1966c), mental arithmetic (Logie et al., 1994) and syllogistic reasoning (Gilhooly et al., 1993) making a strong case for the implication of the central executive in a range of complex cognitive tasks requiring focused attention.

The capacity to divide attention was explored through the work with patients with Alzheimer's disease (AD). Such patients typically suffer from both a pronounced episodic long-term memory deficit and attentional deficits (Perry and Hodges, 1999), which led Baddeley et al. (1991a) to suggest that they might suffer from a central executive impairment. In a study exploring the capacity for dual task performance, the patients were required to combine tasks employing the phonological loop and the visuospatial sketchpad. In both cases the difficulty of the tasks was titrated so that the level of performance on a single task alone matched that of both elderly and young control participants. While the manipulation of level of difficulty of the single task performed alone did not differentially affect AD patients, their dual task performance was dramatically impaired, while it was not affected by age (Logie et al., 2000). These results support the assumption that the capacity to divide attention presents a separable executive capacity.

The relation of the capacity to switch attention to executive processes was extensively tested by Allport et al. (1994). The authors argued that if the capacity to switch attention is an important component of executive control, then switching cost should interact with the executive demand of the tasks that were being switched. The observed pattern of results did not confirm the hypothesis, showing a relatively constant cost of switching across conditions.

Another test of the capacity of attention switching as an executive process was carried out by Baddeley et al. (2001). The authors studied the performance of subjects on a switching task under dual-task conditions employing various articulatory suppression and central executive tasks. The results showed a consistent though small role of the central executive in attentional switching. Perhaps more importantly, the study revealed a significant effect of articulatory suppression on attention switching in some conditions. The results seem to reveal an important contribution of the phonological loop to the control of a specific verbally-based action, possibly through maintenance of an action switching program. The same pattern of results was recently obtained by Saeki and Saito (2004). These authors also reported a significant increase in switch costs when task switching was accompanied by articulatory suppression in the absence of external task cues, while concurrent tapping had no effect.

Taken together the results imply that task switching might be better considered as a result of a number of different processes rather than a single executive process. Most authors agree with such a multi-component notion of task switching (e.g. De Jong, 2000; Goschke, 2000; Rubinstein et al., 2001; Saeki and Saito, 2004). Two capacities are assumed: the maintenance of a task switch program, and the capacity to execute or activate the appropriate task. Of these, the central executive seems more likely to be involved in the latter, while the phonological loop may be a useful means of storing and operating a task-specific internal program in the absence of external cues.

The fourth component capacity of the central executive as proposed by Baddeley (1996) is the ability to relate the content of working memory to long-term memory. The interface between the working memory subsystems and long-term memory has been subsequently transferred to a new component of working memory, the episodic buffer, which will be addressed separately.

The role of the central executive in working memory tasks and processes. In exploring multicomponent working memory, most of the early studies focused on the properties of the slave subsystems, probing the forms of representation and mechanisms of maintenance they utilize. At least implicitly, most studies assumed that some form of executive control was involved in the performance of the tasks employed, but few addressed the specific contribution of the central executive directly. Studying the effect of concurrent visual span for letters or patterns on a visual matrix or verbally based imagery task, Logie et al. (1990) found strong differential interference. A visuospatial imagery task was much more severely disrupted by concurrent memory span for visually presented patterns than by span for visually presented letter sequences while the converse was true for a verbal task. In addition however, both the visual and verbal memory span tasks interfered with both the visuospatial and the verbal concurrent tasks, although to a smaller degree. The authors concluded that the dual task design revealed the existence of both *specialist* resources that are differentially employed in different versions of the tasks, and a *general-purpose* resource employed in all the tasks used. The study therefore implicates the central executive in the dual task performance of the tasks studied.

A question that remained open in the Logie et al. (1990) study was whether the central executive is involved in coordinating the dual task performance, or do the imagery tasks themselves draw on general processing resources in addition to specialist resources. To tackle this question Salway and Logie (1995) used a random letter generation task in addition to articulatory suppression and spatial suppression tasks, designed to disrupt the central executive, the phonological loop and the visuospatial sketchpad, respectively. Results showed that random generation produced notably greater interference than either spatial or articulatory suppression for both visual and verbal versions of the imagery task. Further analysis additionally revealed a tendency for stronger interference with the visual than the verbal task. The authors concluded that in comparison to simple temporary storage of visual or spatial information, the generation of mental images from heard instructions requires general purpose resources ascribed to the central executive.

The contribution of the central executive to image manipulation was further explored in a dual task study by Bruyer and Scailquin (1998). In this study the authors explored the impact of random letter generation on image generation and maintenance. The results revealed that while there was no effect on passive maintenance, both image manipulation tasks showed strong interference from the concurrent random letter generation task. A more recent study by Mohr and Linden (2005) explored the effect of random word generation on manipulation of colors and angles in working memory. The results confirmed that the central executive task significantly interferes with both color and angle manipulation while it does not affect their simple maintenance. An additional important finding was that while both color and angle manipulation tasks seem to draw on processing resources related to the central executive, the subjects were able to perform them in parallel without noticeable decline in performance.

Working memory and visual selective attention. As reported in the section on spatial visual attention, a number of recent studies have explored the relation of working memory to visual selective attention. A point worth noting is that the majority of studies did not specifically address the role of the central executive. There are a number of ways in which working memory might be involved in visual selective attention tasks. Most authors agree that the stimuli presented in the task need to be stored in working memory to be able to perform the task (Bundesen, 1990). The representations in working memory are assumed to serve as templates that enable the selective activation of targets and inhibition of distractors (Duncan and Humphreys, 1989; Desimone, 1996) based on active maintenance of stimulus priorities (Lavie, 2005).

As already mentioned, initial dual task explorations of visual search showed that concurrent maintenance of verbal (Logan, 1978) or visual material (Woodman et al., 2001; Oh and Kim, 2004) does not impair the efficiency of visual search. Does that mean that working memory is not needed in tasks employing selective visual attention? Three lines of research provide evidence for a resounding "no" in reply to this question. First, studies employing a concurrent spatial working memory task show that maintenance of spatial information significantly interferes with visual search (Woodman and Luck, 2004; Oh and Kim, 2004). It seems that spatial working memory and visual search are intimately related. The exact nature of relation however still needs to be determined.

Second, a study by Han and Kim (2004) shows that manipulation within working memory significantly interferes with concurrent visual search. In their study participants were asked to either count backwards from a given number or to sort a given string of letters while performing a visual search task. The dual-task condition in both cases reduced the speed of the visual search task as reflected by significantly steeper search slopes compared with the search-alone condition. No effect of interference was observed when visual search was combined with a simple working memory maintenance task. The authors concluded that visual search might require working memory resources related to the executive functions.

Third, in a series of studies, Lavie (2005; De Fockert et al., 2001; Lavie et al., 2004; Lavie and De Fockert, 2005) have shown that even a simple working memory maintenance task significantly interferes with visual attention tasks when potent distractors that strongly compete with targets are present. The authors have found higher interference from distractors under high vs. low working memory load (memory for digit order) in a Stroop-like task requiring subjects to classify famous written names as pop stars or politicians while ignoring distractor faces (De Fockert et al., 2001). The same pattern of results was observed in a flanker response-competition task combined with digit set maintenance (Lavie et al., 2004). Similarly, the authors have shown greater interference from a salient but task irrelevant color singleton in a visual search task in a condition of high vs. low working load (Lavie and De Fockert, in press). Based on this cumulative evidence the authors argue that working memory is crucial for maintaining task-processing priorities between relevant and irrelevant stimuli. This enables goal-directed control of selective attention and the rejection of irrelevant distractors. Such active control, however, only seems to be needed when a conflict between targets and a salient competing distractor needs to be resolved.

Conclusion. While the central executive may have initially seemed to be simply a convenient homunculus, recent empirical work clearly demonstrates that a number of potentially separable executive functions and capacities can be distinguished. These in turn are importantly involved both in the functioning of the storage components of working memory, and in a number of more general cognitive processes. In the realm of working memory tasks, executive processes seem to be involved whenever information within the stores needs to be manipulated. Simple representation and maintenance on the other hand may be independent of the central executive, unless it requires the complex binding and integration of information. In complex cognitive abilities, the central executive seems to be mostly involved as a source of attentional control, enabling the focusing of attention, the division of attention between concurrent tasks and as one component of attentional switching. In many of these functions central executive is supported by other components of working memory. The phonological loop seems to provide one form of convenient storage of execution programs, while the visuospatial sketchpad seems to be involved in guiding visual and spatial attention. Assessing the contribution of the central executive to the performance of complex tasks has only recently gained in popularity and requires further exploration, but the results gathered so far represent a useful first step in elucidating the contribution of working memory to general cognition.

The episodic buffer

The episodic buffer is the latest addition to the multi-component model of working memory (Baddeley, 2000). It represents a separate storage system of limited capacity using a multi-modal code. It is episodic by virtue of holding information that is integrated from a range of systems including other working memory components and long-term memory into coherent complex structures: scenes or episodes. It is a buffer in that it serves as an intermediary between subsystems with different codes, which it combines into unitary multi-dimensional representations. The integration and maintenance of information within the episodic buffer depends on a limited capacity attentional system, namely the central executive. The retrieval of information is based on conscious awareness, which binds together complex information from multiple sources and modalities. Together with the ability to create and manipulate novel representations, it creates a mental modeling space that enables the consideration of possible outcomes, hence providing the basis for planning future action.

The episodic buffer was postulated to account for a range of empirical data that could not be explained using the original tripartite model. In this section we shall therefore first present the issues that episodic buffer was proposed to address. Next we will consider some of the recent studies that have approached the episodic buffer in different ways. We will conclude with the challenges and prospects that the exploration of the new component of working memory is facing.

The problems addressed by the episodic buffer. Throughout the years of exploration of working memory, a number of empirical findings accumulated that failed to be satisfactorily accounted for by the existing three-component model of working memory. While the model assumed that the verbal information in the phonological loop is stored in a purely phonological code, early research already showed that immediate memory for words is sensitive to semantic similarity when the words can be readily combined into meaningful pairs (Baddeley and Levy, 1971). Comparing unrelated verbal material to immediate memory for prose yielded a substantial difference in recall. While subjects successfully recalled about five unrelated words, they were able to recall up to 16 words when tested using sentences (Baddeley et al., 1987). The existing model offered no explanation for the advantage in recall provided by the meaningful relation between words; nor did it provide a mechanism that would enable aggregation of individual items into larger units: the process or *chunking* (Miller, 1956).

The model provided no explanation of how the subsystems of working memory relate to and interface with long-term memory, even though memory span for unrelated words proved to be affected by variables that are ordinarily related to long-term memory, such as word frequency and imageability (Hulme et al., 1995).

The original model also did not explain how information from the two slave subsystems might be bound together, even though a number of studies had shown that simple verbal span can show evidence of combined verbal and visual encoding (Chincotta et al., 1999, Logie et al., 2000). As the two slave subsystems provide separate and independent stores, the question arises how and where is the information combined.

Addressing the question of conscious awareness, Baddeley and Andrade (2000) exposed a similar problem. The authors conducted a study requiring the participants to form images either of a novel array comprising shapes or tones, or images based on long-term knowledge (such as a familiar market scene), while performing concurrent articulatory or spatial suppression. The study revealed that the expressed judgments of vividness reflected a combination of working memory and long-term memory factors. It seems that information from both sources was combined in a way that the tripartite model was not able to explain. The same problem is expressed in the ability to combine old images in novel ways such as imagining a “swan shopping or an ice-hockey-playing elephant” (Baddeley, 2001, pp. 857).

Results from other areas of research were also instructive. A study of densely amnesic patients (Baddeley and Wilson, 2002) revealed that while their delayed recall of prose paragraphs is effectively zero, a few patients still showed excellent immediate recall. Such patients showed a high level of general intelligence and typically had well-preserved executive capacities. It seems that while the delayed recall of prose critically depends on intact long-term memory, immediate recall may be achieved by a separate system, closely related to working memory.

Last but not least, the model was unable to appropriately account for the wealth of research exploring individual differences in working memory as reflected in the working memory span measure developed by Daneman and Carpenter (1980, 1983). The working memory span task was devised to assess the capacity of working memory to simultaneously process and store information. It requires the participants to read and/or verify a sequence of sentences, storing the last word of each sentence, which they must then recall. The measure was shown to correlate strongly with a performance on a wide variety of tasks (see Engle, 1996; Jarrold and Towse, 2006) and was suggested to be virtually equivalent to a measure of general intelligence (Kyllonen and Christal, 1990). It was however, unclear how the task and related findings could be explained by the existing multicomponent model of working memory.

The empirical findings reviewed above presented a strong case for the ability of working memory to integrate and store information from various sources, including the existing subsidiary working memory systems and long-term memory, in a way that would allow their active maintenance and manipulation. The addition of a fourth component, the episodic buffer, enabled the multicomponent model to account for these findings.

Exploration of the episodic buffer. While the above findings motivated the postulation of a novel component of working memory, further research is needed to test and elucidate the model. To explore the episodic buffer and its role in cognition in the same way as the rest of the components of the working memory model, two classes of tasks need to be developed, namely measures of capacity and interference tasks.

Two tasks that seem to employ the use of episodic buffer were used in recent neuroimaging studies (Prabhakaran et al., 2000; Zhang et al., 2004). Prabhakaran et al. (2000) devised a task that required concurrent maintenance of presented letters and locations, both of them being tested independently. When the four locations to be remembered were each represented by one of the four letters, that is when the letter and location were bound, the accuracy of responses to the test stimulus was higher and the reaction times shorter than when letters were presented in a separate position from the locations. In addition, when the probe was congruent (the probe letter was presented in the same position as at presentation), the subject responded faster and with greater accuracy than in the case of incongruent probes. The imaging results, showed right prefrontal activation in the bound condition. The authors proposed that the study provided evidence for a memory buffer that is distinct from the phonological loop or the visuospatial sketchpad, and which allows for the temporary retention of integrated information.

In a similar study, Zhang et al. (2004) asked participants to recall a series of auditorily presented digits and visual locations given either in pseudorandom mixed order or in a separate order, with digits following the positions. Previous research (Penney, 1989; Zhang et al., 1997, 1999) has shown that when auditory and visual stimuli are presented in a mixed order, separate recall of items was much better (12–13 items) than when subject were required to recall the items in the exact order presented (six to seven items). Zhang et al. (2004) replicated the findings by Prabhakaran et al. (2000) in showing greater right prefrontal activation in the task that requested or encouraged integrated representation in working memory.

An additional candidate for a task requiring involvement of the episodic buffer was reported by Zimmer et al. (2003). The authors tested participants' short-term memory for the spatial location of objects. Using a dual-task paradigm, the authors showed that neither DVN nor a spatial tapping task interfered with memory for object locations, while the spatial task significantly interfered with the Corsi spatial short-term memory task and with memory for the location of nonsense figures. The authors concluded that the configuration of the objects is probably reconstructed from perceptual records in the episodic buffer. It should however be noted that DVN might not be an appropriate interference task for visual working memory (see the above section on visual working memory).

The studies reviewed here represent only the first step in the empirical exploration of the episodic buffer. They do however, broadly support the assumption of a separate working memory store that enables the maintenance of information in an integrated multidimensional form and relies upon the processing resources of the central executive.

Conclusion. The proposal of a new component of working memory, the episodic buffer, seems timely, although research on the buffer is still in its infancy and may well prove more challenging than was the study of the phonological loop and visuospatial sketchpad. While behavioral studies of the other two subcomponents of working memory focused on developing simple tasks that would target their basic elements and mechanisms, the study of the episodic buffer by definition depends on tasks that require complex integration of information. Progress in the understanding of the episodic buffer may therefore depend to a larger degree upon multidisciplinary research, as already witnessed by studies in neuropsychology (e.g. Baddeley and Wilson, 2002; Gooding et al., 2005; Kittler et al., 2004), neuroimaging (Prabhakaran et al., 2000; Zhang et al., 2004) and individual differences (Alloway et al., 2004). Due to its close connections to both the phonological loop and the visuospatial sketchpad, specific attention will have to be paid to maintaining a clear conceptual and operational distinction between the proposed subsystems.

Cognitive neuroscience: the connection between brain and cognitive function

When describing a TV remote control, an electrician would be concerned with the exact circuitry employed that enables the emission of either the radio or infrared signal, a chemist would be interested in the compounds that enable the lightness and rigidity of the casing, while the user only wants to know which button to press for the desired effect. Every description of the remote control is valid and needed in its relevant context. Each contributes to the understanding of the remote control and its function. In just the same way, brain and mind can be observed and described at very different levels, each contributing a part of the story, fulfilling different functions and roles. To be able to reach a full understanding of the mind, different levels of description need to be brought together in a congruent fashion. They need to inspire, inform and constrain one another. In trying to achieve this, one needs to be aware of the differences between these levels of analysis, recognizing their individual strengths and weaknesses, and avoiding the dangerous lure of oversimplification.

Our intention was to present a functional model of working memory along with the behavioral properties and capacities it tries to explain. The present review was purposely limited to experimental behavioral data, mapping a functional description of working memory. Experimental behavioral research, however, is not the only line of research that bears upon a functional description of working memory. Human working memory is a system implemented in the brain and therefore constrained by its properties. Carefully planned and executed, studies that include the brain dimension can contribute important test and insights to the development of functional description of any cognitive ability.

Among the most influential approaches to relating functional description of cognitive processes to the brain builds on systematic mapping of mental processes to brain structures. The approach was pioneered by cognitive neuropsychology, relating specific brain damage to accompanying cognitive dysfunctions. Knowing which cognitive processes are disturbed by damage to a specific brain area, allows one to assume not only that a specific function is subserved by that region, but also that the function itself present a distinct functional component of the system. Studies that described patients with severely disrupted ability for immediate recall, but otherwise intact long-term memory and general cognition (e.g. Shallice and Warrington, 1970; Vallar and Baddeley, 1984) supported both the idea of a separate short-term memory store as well as its fractionation into multiple components. Study of brain damaged patients has since supported many other dissociations between subcomponents of working memory and offered additional important insights (for recent reviews see Vallar and Papagano, 2002; Della Sala and Logie, 2002; Mueller and Knight, 2006).

A number of other methods also allow systematic function to structure mapping, among them single cell studies (see Shintaro, 2006), virtual lesioning by transcranial magnetic stimulation (see Mottaghy, 2006), and functional brain imaging techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and source localization using multichannel electroencephalography (EEG) or magnetoencephalography (MEG). While some might be doubtful about the value of such function to structure mapping, comparing neuroimaging to modern day phrenology (e.g. Uttal, 2001), the ability to observe the brain regions being activated by a specific task or condition does present another valuable dependent variable that can be used to augment behavioral studies in testing competing theories and/or generating new ones (Henson, 2005).

Henson (2005) describes two types of inference offered by neuroimaging studies. First, when two experimental conditions result in a qualitatively different pattern of activity over the brain, we can conclude that the two conditions give rise to different functional processes. Second, activity of the same brain regions under different conditions implies the existence of functional processes that are common to both conditions. Both types of inference can be found in the working memory literature. Initial PET and fMRI studies, for instance, found support for the functional separation of the phonological loop and the visuospatial sketchpad by confirming that verbal and spatial working memory tasks activate different brain regions (Paulesu et al., 1993; Jonides et al., 1993; Smith et al., 1996). Such studies also identified separate anatomical regions concerned with short-term phonological storage and rehearsal, in line with the phonological loop model (for a comprehensive review see Baddeley, in press).

When combined with detailed knowledge gained from previous neuroimaging, brain lesion and single cell studies, neuroimaging studies employing well-designed cognitive tasks can provide important contributions to understanding the functional mechanisms and representations used in working memory. One example is a recent study by Curtis et al. (2004; see also Curtis, 2006), which showed that small differences in spatial working memory task can lead to significantly different pattern of brain activation. Coupled with specific knowledge of the regions involved, the authors concluded, that based on the demands of the task, the participants can maintain spatial information either in the form of prepared eye movements or as a perceptual memory of stimulus position. The results compliment and extend the results obtained by behavioral experimental studies (see the section on representation and maintenance in spatial working memory).

Mapping cognitive processes onto brain regions is not of course, the only possible way of informing and constraining functional models of cognition. Knowledge of brain structure and physiology shapes our understanding of computational properties of the brain, allowing us to build comprehensive computational models. Exploration of brain dysfunctions in neurological and psychiatric conditions can also help explain the observed patterns of cognitive impairments, further testing and constraining the functional models of the impaired functions (see Barch, 2006; Honey and Fletcher, 2006). With existing and new methods and research paradigms relating the brain and the mind being constantly developed, the future of multidisciplinary research of working memory indeed seems bright.

General conclusions

We suggest that working memory has proved to be an important part of the cognitive system, providing the ability to maintain and manipulate information in the process of guiding and executing complex cognitive tasks. It can be fractionated into a number of independent subsystems, processes and mechanisms. It can usefully be described as a multicomponent system guided by an executive component consisting of a number of processes that provide attentional control over other components of working memory as well as other cognitive abilities. The subordinate components provide limited capacity memory stores that enable the representation and maintenance of information. Two of the subcomponents are domain specific, providing the ability to hold phonological and visuospatial information in separate stores. A third subcomponent enables the integration of information into complex multi-modal representations linking working memory to long-term memory.

The functional model of working memory we have described might not prove easy to map onto the underlying neuroanatomy. Some have argued (see Postle, 2006; Hazy et al., 2006), that working memory might prove to be an emergent property, a product of the interaction of a highly distributed neuronal system. On a functional level, however, working memory provides a well-defined conceptual system that fulfills its role of presenting, organizing and explaining the existing empirical evidence and, importantly, continues to be fruitful in generating further empirically tractable questions.

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