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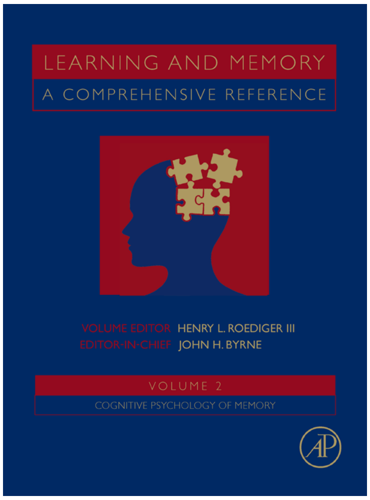

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2.04 Working Memory

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2.04.1 Introduction

A common feature of our everyday mental life is the need to hold information in mind for brief periods of time. We frequently have to remember a new telephone or vehicle registration number, to write down the spelling of an unusual name that has been dictated to us, or to follow spoken instructions to find our destination in an unfamiliar environment. At other times, we need to engage in mental activities that require both temporary storage and demanding cognitive processing. Mental arithmetic provides a good example of this: successfully multiplying two numbers such as 43 and 27 in our heads involves storing not only the numbers but the products of the intermediate calculations, accessing and applying the stored rules of multiplication and addition, and integrating the various pieces of information to arrive at the correct solution. Our conscious experience of the calculation attempt is of a kind of mental juggling, in which we try to keep all elements of the task – the numbers we are trying to remember as well as the calculations – going at the same time. Often, the juggling attempt will fail, either because the capacity of working memory is exceeded, or because we become distracted and our attention is diverted away from the task in hand.

Working memory – which is the term widely used by psychologists to refer to the set of cognitive processes involved in the temporary storage and manipulation of information – supports all of these activities and many more. A useful informal way of conceptualizing working memory is as a mental jotting pad that we can use to record useful material for brief periods of time, as the need arises in the course of our everyday cognitive activities. Although it a valuable and highly flexible resource, working memory has several limitations: its storage capacity is limited, and it is a fragile system whose contents are easily disrupted. Once lost from working memory, material cannot be recovered.

The basic features of working memory are described in this chapter. Leading theoretical accounts of the cognitive processes involved in working memory are described, and key findings and experimental phenomena are outlined. As it is now also known that

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working memory is important not only for the temporary retention of information, but also for the acquisition of more permanent knowledge, theories of how different aspects of working memory mediate learning are also considered in this chapter.

2.04.2 The Working Memory Model

One influential theoretical account of working memory has framed much of the research and thinking in this field for several decades. In 1974, Baddeley and Hitch advanced a model of working memory that has been substantially refined and extended over the intervening period. The influence of the working memory model extends far beyond the detailed structure of its cognitive processes, which are considered in the following sections. The radical claim made by Baddeley and Hitch was that working memory is a flexible multicomponent system that satisfies a wide range of everyday cognitive needs for temporary mental storage – in other words, it does important work for the user. The distinction between short-term memory and working memory is a key element in the philosophy of this approach. The term working memory refers to the whole set of cognitive processes that comprise the model, which as we will see includes higher-level attentional and executive processes as well as storage systems specialized for particular information domains. Activities that tap a broad range of the functions of working memory, including both storage and higher-level control functions, are often described as working memory tasks. The term short-term memory, on the other hand, is largely reserved for memory tasks that principally require the temporary storage of information only. In this respect, short-term memory tasks tap only a subset of working memory processes. Detailed examples of each of these classes of memory task are provided in later sections.

A further key element of the Baddeley and Hitch (1974) approach is its use of dual-task methodology to investigate the modular structure of the working memory system. These researchers have developed a set of laboratory techniques for occupying particular components of the working memory system, which can then be used to investigate the extent to which particular activities engage one or another component. By the logic of dual-task methodology, any two activities that are unimpaired when conducted in combination do not tap common limited capacity systems. In contrast, performance decrements when two tasks are combined indicate that they share a reliance on the same component. This empirical approach has proved invaluable in fractionating working memory into its constituent parts, leading to the most recent version of the working memory model, advanced by Baddeley in 2000 (Baddeley, 2000) (**Figure 1**).

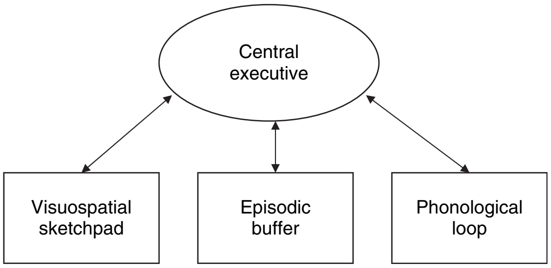

Figure 1 The Baddeley (2000) working memory model.

This model consists of four components. Two of these components, the phonological loop and the visuospatial sketchpad, are slave systems that are specialized for the temporary storage of material in particular domains (verbal and visuospatial, respectively). The central executive is a higher-level regulatory system, and the episodic buffer integrates and binds representations from different parts of the system. The nature of each of these components and associated empirical evidence are described in the following sections. Note also that components of working memory are directly linked with longer-term memory systems in various informational domains. The nature of the interface between working memory and the acquisition of knowledge is considered in later sections of the chapter.

2.04.2.1 The Phonological Loop

Originally termed the articulatory loop by Baddeley and Hitch (1974), the phonological loop is a slave system dedicated to the temporary storage of material in terms of its constituent sounds, or phonemes. The two-component model of the phonological loop advanced by Baddeley in 1986 is shown in **Figure 2**. Representations in the phonological short-term store are subject to rapid time-based decay. Auditory speech information gains obligatory access to the phonological store.

Subvocal rehearsal reactivates serially the contents of the short-term store, in a process that corresponds closely to overt articulation (speaking), but which does

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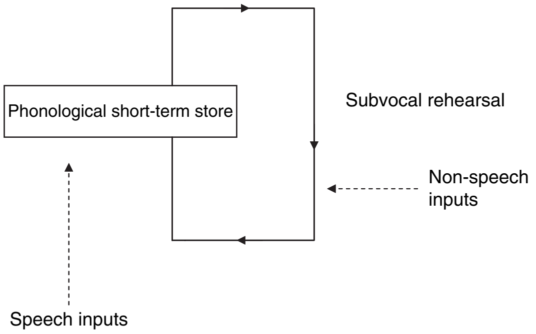

Figure 2 The phonological loop model, based on Baddeley (1986).

not necessarily involve the movement of the speech apparatus or the generation of speech sounds. Representations in the phonological store that are rehearsed before they have time to decay can be maintained in the phonological loop indefinitely, provided that rehearsal continues. Rehearsal consists of the high-level activation of speech-motor planning processes (Bishop and Robson, 1989; Caplan et al., 1992) and is a time-limited process in which lengthier items take longer to activate than short items. Material that is not presented in the form of spoken language but which is nonetheless associated with verbal labels, such as printed words or pictures of familiar objects, can enter the phonological store via rehearsal, which generates the corresponding phonological representations from stored lexical knowledge.

2.04.2.1.1 Empirical phenomena

This fractionated structure to the phonological loop is consistent with a wide range of experimental phenomena from the serial recall paradigm, in which lists of items are presented serially for immediate recall in the original input sequence. Evidence that verbal material is held in a phonological code is provided by the fact that irrespective of whether the memory lists are presented in auditory form or in the form of print, recall is poorer for sequences in which the items share a high degree of phonological similarity (e.g., C, G, B, V, T) than for those which have little overlap in phonological structure (e.g., X, H, K, W, Q). This effect of phonological similarity, first reported by Conrad (1964) and replicated many times subsequently, indicates that serial recall is mediated by phonological representations. Degradation of these representations, possibly due to decay, will thus cause confusion between representations of items with highly similar phonological structures.

The obligatory access of auditory speech information to the phonological loop is demonstrated by the irrelevant speech effect. Serial recall of visually presented verbal items is impaired if spoken items are presented during list presentation, even though participants are told to ignore these stimuli. Moreover, the recall advantage to phonologically distinct over phonologically similar sequences is eliminated under such conditions of irrelevant speech (Colle and Welsh, 1976; Suprenant et al., 1999). This finding indicates that irrelevant speech operates on the same process that gives rise to the phonological similarity effect, so that the unwanted stimuli generate representations in the phonological store that disrupt those of the list items to be recalled.

Evidence for the existence of a distinct subvocal rehearsal process that operates on the contents of the phonological store is provided by other empirical phenomena. An important finding first reported by Baddeley et al. (1975) is that serial recall accuracy is impaired when memory lists contain lengthy items (e.g., aluminum, hippopotamus, tuberculosis) than otherwise matched short items (e.g., zinc, stoat, mumps). Detailed analyses have established that a linear function related recall accuracy to the rate at which participants can articulate the memory sequence: items that are be spoken more rapidly are recalled more accurately, to a commensurate degree. This phenomenon, known as the word length effect, is present for visually and auditorily presented verbal material and is suggested to reflect the serial rehearsal process, which requires more time to re-activate lengthy than short items. As a consequence, representations in the phonological store of lengthy items are more likely to have decayed between successive rehearsals, leading to decay and loss of information.

Support for this interpretation is provided by findings that the word length effect disappears if participants engage in articulatory suppression by saying something irrelevant such as “hiya, hiya, hiya” during presentation of the memory list, for both visually and auditorily presented lists (Baddeley et al., 1975, 1984). These results can be simply explained. Having to engage in irrelevant articulation during a memory task prevents effective rehearsal of the memory items themselves – it simply is not possible to say one thing and to rehearse subvocally something else. As rehearsal is prevented in this condition, there can be no further impairment of recall with lengthy as opposed to short memory items, as this effect is also tied to the rehearsal process.

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It should be noted that because visually presented material requires rehearsal to access the phonological store, preventing rehearsal via articulatory suppression should also eliminate the phonological similarity effect with visual presentation, as the material will not reach the store for the similarity-based interference to occur. This prediction has been supported by findings from many studies (Murray, 1968; Peterson and Johnson, 1971).

The claim that the word length effect arises only from subvocal rehearsal has not gone uncontested. Lengthier items are slower not only to rehearse but also to recall, and there is convincing evidence that the increased delay in recalling longer items is one cause of lower performance, probably due to the increased opportunity for time-based decay of the phonological representations. Cowan et al. (1992) employed mixed lists composed of both short and long words to investigate the effects of recall delay. They found a linear relation between the amount of time elapsing from the beginning of the recall attempt and the accuracy of recall, with recall declining as the delay increased (see also, Cowan et al., 1994). One possibility is that the word length effect is multiply determined, and that the slower rate of rehearsal for long than short items is just one of several mechanisms causing lower levels of recall accuracy for lists composed of lengthy stimuli.

Debate concerning the detailed processes underpinning experimental phenomena such as the effects of word length and irrelevant speech (e.g., Neath et al., 2003; Jones et al., 2006) continues, and will in time result in a fuller understanding of the precise mechanisms of serial recall. More generally, though, the broad distinction between the short-term store and rehearsal subcomponents of the phonological loop has received substantial support from several different empirical traditions. It is entirely consistent with evidence of developmental fractionation of the subcomponents of the phonological loop during the childhood years (see Gathercole and Hitch, 1993; Palmer, 2000, for reviews). The phonological store appears to be in place by the preschool period: by roughly 4 years of age, children show adult-like sensitivity to the phonological similarity of the lists items for auditorily presented material (Hitch and Halliday, 1983; Hulme and Tordoff, 1989). The subvocal rehearsal strategy, in contrast, emerges at a later time, typically after 7 years of age. Flavell et al. (1967) observed many years ago that very young children do not show the overt signs of rehearsal, such as lip movements and overt repetition, that characterize older children. Children below 7 years of age are also not disrupted by recalling memory sequences composed of lengthy rather than short items (Hitch and Halliday, 1983), although word length effects do emerge in children as young as 5 years of age if they are trained in the use of rehearsal strategies (Johnson et al., 1987). Also, there is also no consistent association between the articulatory rate and memory span in 5-year-old children, although strong links are found in adults (Gathercole et al., 1994a). Together, these findings indicate that although the phonological store is present at a very early point in children, the use of subvocal rehearsal as a means of maintaining the rapidly decaying representations in the store emerges only during the middle childhood years.

The phonological store and rehearsal process also appear to be served by distinct neuroanatomical regions of the left hemisphere of the brain. Evidence from patients with acquired brain damage resulting in impairments of verbal short-term memory indicates that short-term phonological storage is associated with the inferior parietal lobule of the left hemisphere, whereas rehearsal is mediated by Broca's area, in the left premotor frontal region (see Vallar and Papagno, 2003; Muller and Knight, 2006, for reviews). Findings from neuroimaging studies using methods such as positron emission tomography and functional magnetic resonance imaging to identify the areas of the brain activated by verbal short-term memory tasks in typical adult participants have further reinforced the neuroanatomical distinction between the phonological store and rehearsal (see Henson, 2005, for review).

2.04.2.1.2 A computational model of the phonological loop

Despite its simplicity, the Baddeley (1986) model of the phonological loop is capable of explaining much of the evidence outlined in the preceding section and several other experimental phenomena. It does, however, have one notable shortcoming as a model of serial recall. Although this paradigm requires the accurate retention of both the items in the memory list and their precise sequence, the model focuses exclusively on the representation of item information and therefore fails to account for how the serial order of list items is retained in the phonological loop. As a consequence, it cannot accommodate many detailed aspects of serial recall behaviour. One important characteristic of serial recall is the serial position function, the asymmetric bow-shaped curve that arises from high levels of accuracy of recalling initial

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list items (the primacy effect), relatively poor recall of mid-list items, and a moderate increase in accuracy for items at the end of the sequence (the recency effect). Another key finding is that the most common category of errors in serial recall is order errors, in which items from the original position migrate to nearby but incorrect positions in the output sequence (Bjork and Healy, 1974; Henson et al., 1996). The Baddeley (1986) model of the phonological loop provides no explanation of either of these features of verbal short-term memory.

Burgess and Hitch (1992) addressed this problem by developing and implementing a connectionist network model that incorporated a mechanism for retaining the serial order of items in addition to temporary phonological representations and an analog of rehearsal that corresponds to the phonological loop. The structure of the model is shown in **Figure 3**. It consists of four separate layers of nodes that represent input phonemes, words, output phonemes, and a context signal. Serial order is encoded by associating the activated item representation with a slowly evolving context signal containing a subset of active nodes that change progressively during presentation of the list, and can be conceptualized as a moving window representing time such that successive context states are more similar to one another than temporally distant states. Presentation of an item causes temporary activation of input phoneme nodes, word nodes, and output phoneme nodes via existing interconnections. When one item node succeeds in becoming the most active, a temporary association is formed between the winning item node and currently active context nodes. The item node is then suppressed, allowing the same process to be repeated for the next item in the sequence. In this model, rehearsal consists of feedback from the output phonemes (activated following selection of the winning item node) to the input phonemes.

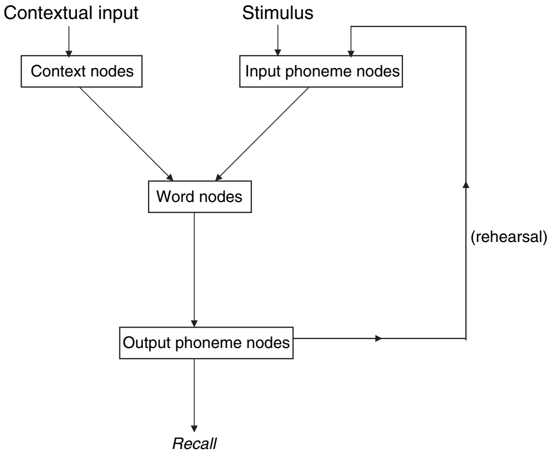

Figure 3 Simplified architecture of the Burgess and Hitch (1992) network model of the phonological loop.

At recall, the original context signal is repeated and evolves over successive items in the same way as at input. For each signal, item nodes receive activation based on their initial pairing with context in the original sequence, and the winning item is selected and activates consistent output phonemes. Noise is added to this final selection process to induce errors. Where serial order errors do occur – that is, incorrect item nodes are selected – they tend to migrate to target-adjacent positions as a consequence of the high degree of overlap in the context nodes active in successive context states.

In addition to generating the classic experimental phenomena associated with the phonological loop such as the phonological similarity, word length, and articulatory suppression effects, this model simulates many of the features of serial order behavior that the phonological loop model on which it was based could not address. Consider first the serial position function. Primacy effects arise largely from the greater number of rehearsals received by early list items, and recall of both initial and final items is enhanced by the reduced degree of order uncertainty at these terminal list positions. A preponderance of order errors is also readily generated because context signals, like item representations, degrade with time. Thus on some occasions, the retrieved item representation will have been associated with an adjacent context signal, yielding recall of a list item at an incorrect output position. When items do migrate in simulations of the model, they show the bell-shaped migration function in which the distances traveled in the sequence are usually small rather than large, which has also been established in the behavioral data.

2.04.2.1.3 The phonological loop and language

Although the cognitive processes underpinning the phonological loop are well understood, one puzzle for many years was exactly why this system exists. It may have turned out to be useful for remembering telephone numbers, but why do we have the system in the first place? A number of possibilities were considered. One plausible hypothesis was that the phonological loop acts as a buffer for planned speech.

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The presence of a phonological output buffer that stores the retrieved phonological specifications of intended lexical items and enables the smooth and rapid production of speech has long been recognized as a logical necessity by speech production theorists (e.g., Bock, 1982; Romani, 1992). There is, however, little evidence that the phonological store fulfills this function (see Gathercole and Baddeley, 1993 for review). It has consistently been found that adult neuropsychological patients with very severe deficits of verbal short-term memory leading to memory spans of only one or two items can nonetheless produce spontaneous speech normally: utterance length rates of hesitations and self-corrections are comparable to those of control adults (Shallice and Butterworth, 1977).

A second hypothesis was that the phonological loop provides an input buffer to incoming language that is consulted in the course of normal comprehension processes (Clark and Clark, 1977). Once again, findings from adult short-term memory patients provided the opportunity to test this hypothesis. The prediction was clear: if short-term memory plays a significant role in comprehension, the very low memory span of short-term memory patients should lead to substantial impairments in processing the meaning of language. Findings from many research groups and many different patients provided little support for this prediction. Despite severe deficits in phonological loop functioning, short-term memory patients typically had few difficulties in processing sentences for meaning, except under conditions in which lengthy, unusual, and ambiguous syntactic structures were used, or the sentences were essentially memory lists (see Vallar and Shallice, 1990; Caplan and Waters, 1990; Gathercole and Baddeley, 1993; for reviews). It therefore appears that although under most circumstances the language processor operates online without recourse to stored representations in the phonological loop, these representations may be consulted in an off-line mode to enable backtracking and possible re-analysis of spoken language under some conditions (McCarthy and Warrington, 1987).

There is, however, one area of language functioning in which the phonological loop appears to play a central role, and that is in learning the sound structure of new words. Evidence from many sources converges on this view. Studies of typically developing children have consistently found close and selective associations between measures of verbal short-term memory and knowledge of both native and foreign language vocabulary (e.g., Gathercole and Baddeley, 1989; Service, 1992; Cheung, 1996; Masoura and Gathercole, 1999). The accuracy of nonword repetition – in which a child hears a spoken nonword such as woogalamic and attempts to repeat it immediately – is particularly highly correlated with vocabulary knowledge, although so too are more conventional measures of verbal short-term memory such as digit span (Gathercole et al., 1994b). A similar link is found between verbal memory skills and the rate of learning nonwords in paired-associate learning paradigms, in which participants learn to associate unfamiliar phonological forms with either novel objects (Gathercole and Baddeley, 1990a, used toy monsters with names such as Pimas), unrelated words (such as fairy-kipser), or semantic attributes (e.g., bleximus is a noisy, dancing fish). Both of the latter examples are from a study reported by Gathercole et al. (1997), in which the phonological memory skills of the participating 5-year-old children were in contrast found to be independent of the ability to learn word–word pairs.

Further evidence that the phonological loop is involved in the long-term learning of phonological structures in particular has been provided by the study of individuals with developmental or acquired deficits in language learning. Specific language impairment (SLI) is a condition in which children fail to develop language at a normal rate despite normal intellectual function. Word learning represents a particular problem for affected children. It has consistently been found that children with SLI have substantial impairments of nonword repetition and of other measures of verbal short-term memory (e.g., Gathercole and Baddeley, 1990b; Bishop et al., 1996; Archibald and Gathercole, 2006). A corresponding neuropsychological patient, PV, had a severe deficit of the phonological loop, and was found to be completely unable to learn word–nonword pairings such as rose–svieti, but performed within the typical range on a word–word learning task (Baddeley et al., 1988). Experimental studies of paired-associate learning with normal adult participants have shown that word–nonword learning is disrupted by variables known to interfere with phonological loop functioning, such as phonological similarity and articulatory suppression (Papagno et al., 1991; Papagno and Vallar, 1992). In contrast, learning of word–word pairs is not influenced by these variables.

On this basis, it has been proposed that the primary function of the phonological loop is to support

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learning of the sound structures of new words in the course of vocabulary acquisition (Baddeley et al., 1998b). It is suggested that initial encounters with the phonological forms of novel words are represented in the phonological short-term store, and that these representations form the basis for the gradual process of abstracting a stable specification of the sound structure across repeated presentations (Brown and Hulme, 1996). Conditions that compromise the quality of the temporary phonological representation in the phonological loop will reduce the efficiency of the process of abstraction and result in slow rates of learning. In a recent review of this theory and associated evidence, Gathercole (2006) has suggested use of the phonological loop to learn new words is a primitive learning mechanism that dominates at the early stages of learning a language and remains available as a strategy throughout life. However, once a substantial lexicon is established in a language, word learners increasing rely on lexically mediated learning of new words, thereby building on the phonological structures that they have already acquired.

2.04.2.1.4 Summary

The phonological loop model advanced by Baddeley (1986), consisting of a short-term store and a subvocal rehearsal process, is the most influential current account of verbal short-term memory. Convergent evidence for the model is provided from a range of research traditions including experimental cognitive psychology, developmental psychology, neuropsychology, and neuroimaging. A similar diverse range of findings indicate that the phonological loop plays a key role in vocabulary acquisition (Baddeley et al., 1998; Gathercole, 2006).

The successful implementation of the model in the form of a connectionist network by Burgess and Hitch (1992) is an important development that has stimulated competing computational models of serial recall with distinct architectures. The network model has also been further developed to simulate learning of novel sequences by the phonological loop (Burgess and Hitch, 1999). The availability of detailed models of short-term memory and the reciprocal stimulation of empirical findings and computational simulations is a sign of advanced theoretical development that is in large part due to the guiding influence of the phonological loop concept on this field over many years.

2.04.2.2 The Visuospatial Sketchpad

2.04.2.2.1 Theory and empirical phenomena

The second slave system of the working memory model is the visuospatial sketchpad, specialized in the storage and manipulation of information that can be represented in terms of either visual or spatial characteristics. Short-term memory for visuospatial material is associated with increased activity in the right hemisphere regions of the inferior prefrontal cortex, anterior occipital cortex, and posterior parietal cortex, and acquired damage to these regions of the brain leads to selective deficits in remembering these domains of material (see Gathercole, 1999, for review).

Several tasks have been designed to tap the visuospatial sketchpad. These include recognizing the pattern of filled squares in a two-dimensional grid (Phillips and Christie, 1977; Wilson et al., 1987), remembering the order in which a set of blocks are tapped (often known as the Corsi blocks task), using a grid to generate a mental image corresponding to a set of spatial instructions (Brooks, 1967), and recalling the path drawn through a maze (Pickering et al., 2001).

Like its sister slave system the phonological loop, the sketchpad has now been fractionated into two distinct but interrelated components: A visual store or cache that preserves the visual features of perceived or internally generated objects and a spatial or sequential component that may serve a recycling function analogous to subvocal rehearsal (Logie, 1995). The strongest evidence for the separation of the sketchpad into these two components is provided by studies of neuropsychological patients with acquired brain lesions resulting in selective impairments of visual storage but preserved spatial short-term memory (Hanley et al., 1991) and converse deficits in spatial but not visual short-term memory (Della Sala et al., 1999; Della Sala and Logie, 2003).

Dual task studies have played an important role in illuminating the functional organization of the visuospatial sketchpad. One popular method for tapping the capacity for the generation and temporary storage of spatial material is the Brooks (1967) task, in which the participant is presented with a 4 × 4 empty grid in which one particular cell was designated as the starting square. The experimenter then gives a series of verbal instructions which participants are encouraged to remember by mentally filling in the grid, as shown in **Figure 4**. Following the

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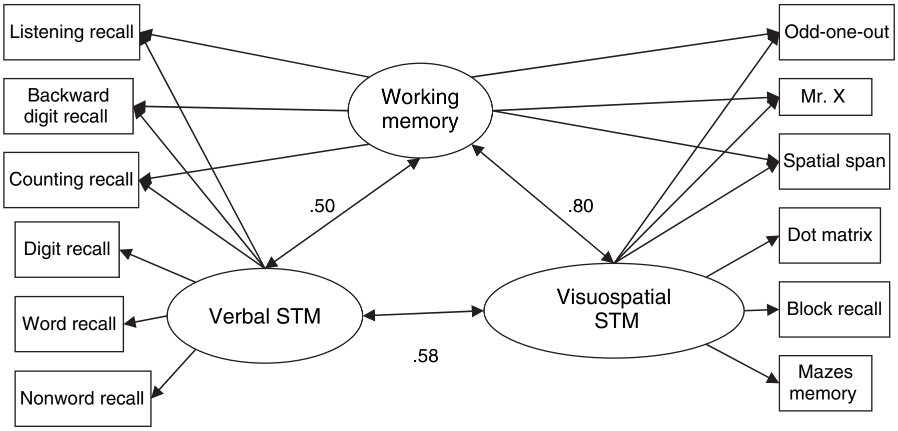

Figure 4 Measurement model of working memory, based on data from children aged 4–11 years. STM, short-term memory. From Alloway TP, Gathercole SE, and Pickering SJ (2006) Verbal and visuo-spatial short-term and working memory in children: Are they separable? *Child Dev.* 77: 1698–1716; used with permission from Blackwell Publishing.

instructions, participants recall the sequence by filling in the grid with the numbers. This condition facilitates the use of spatial imagery and hence the visuospatial sketchpad. In a control condition which does not encourage the use of such spatial imagery, the spatial terms up, down, left, right were replaced by the nonspatial adjectives good, bad, slow, and fast to yield nonsensical sentences. Presumably, recall in this condition was supported by the phonological loop rather than the sketchpad.

Evidence that participants use mental imagery to mediate performance in the spatial but not the nonsense condition is provided by the superior levels of recall accuracy in the former condition (Brooks, 1967). In a systematic study of the effects of concurrent activities on memory performance in the two cases, Baddeley and Lieberman (1980) reported further evidence that distinct components of working memory are employed in the two conditions. Performing a concurrent task – tracking an overhead swinging pendulum – disrupted recall in the spatial but not the nonsense condition. Thus, spatial recall appears to be selectively impaired by the encoding of unrelated spatial content, consistent with the employment of a spatial code to mediate recall performance.

Subsequent investigations indicate that eye movements may play a key role in the maintenance of spatial images in the sketchpad. Postle et al. (2006) reported a series of experiments showing that voluntary eye movements impair memory for spatial locations but not for nonspatial features of visual objects, providing further support for a distinction between visual and spatial components of the sketchpad. Other studies have shown that the engagement of other movement systems such as hands (finger tapping), legs (foot tapping), and arms exerts similar disruptive influences on memory for spatial sequences such as Corsi block recall (e.g., Smyth and Scholey, 1988). It therefore appears that the maintenance of spatial representations in the sketchpad is supported by a central motor plan that is not specific to any particular effector system, by which is recruited the planning and execution of movements in the full range of motor systems.

There is some evidence that the visual storage component of the spatial sketchpad is selectively disrupted by the concurrent perception of irrelevant visual features. In a series of studies reported by Quinn and McDonnell (1996), memory for detailed visual characteristics was selectively impaired by visual noise that corresponded to a randomly flickering display of pixels similar to an untuned television screen that participants were required to view but asked to disregard. This finding is important, as it is directly analogous to the irrelevant speech effect in verbal serial recall (Colle and Welsh, 1976), which has been interpreted as reflecting obligatory access to the short-term store component of the phonological loop for auditory speech material.

One interpretational problem raised by many studies of visuospatial short-term memory is the extent to which these and other similar tasks reflect a genuinely distinct component of working memory, or alternatively draw on the more general resources of the central executive. The central executive, which is described in more detail in the following section, is a

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limited-capacity domain-general system capable of supporting a wide range of cognitive activities. Several different lines of evidence indicate that the central executive plays a major role in many visuospatial short-term memory tasks. Performance on visual storage tasks has been found to be strongly disrupted by concurrent activities that lack an overt visuospatial component but which are known to tax the central executive, such as mental arithmetic (Phillips and Christie, 1977; Wilson et al., 1987). Also, studies of individual differences have consistently shown that measures of visuospatial short-term memory are much more closely associated with performance on central executive tasks than are phonological loop measures, in both typically developing children (Gathercole et al., 2004a, 2006a; Alloway et al., 2006) and in a clinical study of adults with bipolar mood disorder (Thompson et al., 2006).

2.04.2.2.2 Summary

Although current understanding of the detailed cognitive processes involved in visuospatial short-term memory is less well advanced than that of the phonological loop, two basic facts have now been established. First, the sketchpad functions independently of the phonological loop – it is associated with activity in the right rather than the left hemisphere of the brain and is selectively disrupted by concurrent activities that do not influence the phonological loop. Second, the processes involved in manipulating and storing visual features and spatial patterns appear to be distinct from one another, again showing neuropsychological and experimental dissociations. It is rather less clear to what extent the visuospatial sketchpad represents a distinct component of working memory that is dissociable from the central executive.

2.04.2.3 The Central Executive

At the heart of the working memory model is the central executive, responsible for the control of the working memory system and its integration with other parts of the cognitive system. The central executive is limited in capacity, and is closely linked with the control of attention and also with the regulation of the flow of information within working memory, and the retrieval of material from more permanent long-term memory systems into working memory. Neuroimaging studies indicate that the frontal lobes of both hemispheres of the brain, and particularly of the prefrontal cortex, are activated by activities known to tax the central executive (See Collette and Van der Linden, 2002; Owen et al., 2005, for reviews).

2.04.2.3.1 The supervisory attentional system

In 1986, Baddeley suggested that central executive may correspond in part at least to the model of the supervisory attentional system (SAS) advanced by Shallice (1982) to explore the control of attention in action. The SAS has two principal components. The contention scheduling system consists of a set of schemas, which are organized structures of behavioral routines that can be activated by either internally or externally generated cues. When a schema reaches a particular level of activation, it is triggered and the appropriate action or set of actions is initiated. Thus, we have schemas that govern all our skilled behaviors: walking and talking, breathing and jumping, opening doors and using a telephone. Schemas can be hierarchically organized. Skilled car drivers, for example, will have a driving schema that is composed of linked subschemas such as steering and braking schemas. Many of our actions are governed by the automatic activation of these schemas in response to environmental cues. So, once we are behind the wheel of a moving car, the sight of a red brake light in the car in front will probably be sufficient to trigger the automatic activation of the braking subschema. Activation levels of all incompatible schemas (such as the accelerating schema, in this case) are inhibited when a schema is triggered.

The second component, the SAS, controls behavior via a very different process. The SAS can directly activate or inhibit schemas, thereby overriding their routine triggering by the contention scheduling system. The intervention of the SAS corresponds to volitional control and prevents us from being endless slaves to environmental cues – it allows us to choose to change the course of our actions at will. However, because the SAS is a limited capacity system, there are finite limits on the amount of attentional control we can apply to our actions.

Baddeley's (1986) suggestion was that the central executive corresponds to the limited-capacity SAS. He also proposed that two types of behavioral disturbance associated with damage to the frontal lobes arise from malfunctioning of the central executive, and coined the term dysexecutive syndrome to describe this disorder. These neuropsychological patients are typically characterized by one of two

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possible types of behavior. Perseveration is a form of behavioral rigidity in which the individual continually repeats the same action or response. An example would be greeting a newcomer by saying "Hello" and then continuing to make the same response many times to the same individual, increasingly inappropriately. Distractibility consists of unfocused behavior in which the individual fails to engage in meaningful responses but may, for example, continuously walk around a room manipulating objects. Baddeley suggested that such individuals have an impairment in central executive resources that reduces their capacity for volitional control of behavior via the SAS, which is instead dominated by the contention scheduling system. Perseveration results when a schema becomes highly activated and cannot be effectively inhibited by the SAS to allow the triggering of other appropriate behaviors, and distractibility results from the background triggering of behavior by environmental cues with no overriding focus by the SAS.

This conceptualization of the central executive has proved useful in guiding the development of laboratory tasks that engage the central executive. One such task is random generation (Baddeley, 1986). In a typical task, the participant is required to generate in a random manner exemplars from a familiar category, such as digits or letters, paced by a metronome. The importance of generating random sequences rather than stereotyped ones such as 1, 2, 3 or a, b, c is emphasized. In 1998, Baddeley et al. (1998a) conducted a series of experiments to investigate the hypothesis that the central executive is needed to intervene to override the activation of stereotyped response sequences in this task. There were several key findings consistent with this view. First, the degree of randomness of the sequences generated by the participants diminished (i.e., the responses became more stereotyped) when the generation rate was increased. This result indicates that the randomness of the responses was constrained by a limited capacity process. Second, the degree of randomness of the generated sequences was not impaired when the task was combined with other activities requiring stereotyped responses such as counting, but was substantially disrupted by nonstereotyped concurrent activities such as maintaining a digit load or generating exemplars of semantic categories. Applying the logic of dual-task methodology, it appears that both tasks tap a common limited-capacity mechanism, the central executive.

2.04.2.3.2 Complex memory span

The central executive also plays a key role in complex memory span tasks, which require both processing and storage. The first reported complex span task, reading span, was developed by Daneman and Carpenter in 1980. In this task, participants must read aloud each of a sequence of printed sentences, and at the end of the sequence they must recall the final word of each sentence in the same order as the sentences were presented. The number of sentences read on each trial is then increased until the point at which the participant can no longer reliably recall the sequence of final words. Findings from this task were impressive – complex memory span scores were highly correlated with the performance of the participating college students on their scholastic aptitude tests completed on entry to college. Importantly, the correlations with scholastic aptitude were considerably higher than those found with storage-only measures of verbal short-term memory.

A range of other complex span paradigms have been subsequently developed, all sharing the common feature of requiring both memory storage while participants are engaged in significant concurrent processing activity. A listening span version of the reading span test in which the sentences were heard rather than read by participants was employed by Daneman and Carpenter (1983), and was found to be correspondingly associated with academic abilities. Complex span tasks suitable for use by young children have also been developed. One popular task is counting span, in which the child has to count the number of elements in a series of visual displays, and at the end of the sequence to recall the totals of each array, in the order of presentation (Case et al., 1982). The odd-one-out task (Russell et al., 1996; Alloway et al., 2006) is a complex memory span task that requires visuospatial rather than verbal storage and processing (see also, Shah and Miyake, 1996). Participants view a series of displays each containing three unfamiliar objects, two identical and one different. The task is to point to the location of the odd one out, and then at the end of the sequence to recall the sequence of spatial locations of the different items. In other complex span tasks, the material to be stored is distinct from the contents of the processing activity. An example of one such task is operation span (Turner and Engle, 1989), in which participants attempt to recall digits whose presentation is interpolated with a sequence of simple additions that must be completed.

Despite the large degree of variation in both the processing and storage demands of the different

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complex memory span tasks, a highly consistent pattern of findings has emerged. Performance on such tasks is strongly related to higher-level cognitive activities such as reasoning and reading comprehension (e.g., Kyllonen and Christal, 1990; Engle et al., 1992), and also to key areas of academic achievement during childhood such as reading and mathematics (e.g., Swanson et al., 1996; Hitch et al., 2001; Jarvis and Gathercole, 2003; Gathercole et al., 2004b, 2006a; Geary et al., 2004; Swanson and Beebe-Frankenberger, 2004). In the majority of these studies, associations with learning were much higher for complex memory span measures than measures such as digit span of verbal short-term memory. Corresponding closer links with measures of intellectual functioning in adulthood such as reading comprehension, scholastic aptitude, and fluid intelligence have also been consistently found in adult populations (for reviews, see Daneman and Merikle, 1996; Engle et al., 1999b).

In order to understand why complex span measures of working memory performance are so strongly associated with learning abilities and other measures of high-level cognition, it is necessary first to consider what cognitive processes these measures tap. It has been suggested that the processing portions of these tasks are supported by the domain-general resources of the central executive, whereas the storage requirements are met by the respective domain-specific slave system (Baddeley and Logie, 1999). By this view, both the central executive and the phonological loop contribute to performance on verbal complex span tasks such as reading span, listening span, and counting span, whereas performance on visuospatial complex span tasks is mediated by the central executive and the visuospatial sketchpad.

There is now substantial evidence to support this proposal. A common processing efficiency factor has been found to underlie both verbal and visuospatial complex memory tasks (Bayliss et al., 2003). Two recent studies have investigated the latent factor structure underlying individuals' performance on both simple (storage-only) and complex span measures in both the verbal and visuospatial domains, in children (Alloway et al., 2006) and in adults (Kane et al., 2004). In both cases, the best-fitting model is a structure consisting of distinct verbal and visuospatial short-term storage components (corresponding to the phonological loop and visuospatial sketchpad, respectively), plus a domain-general factor corresponding to the central executive. A summary of the factor structure of the model from Alloway et al. (2006) is shown in **Figure 4**. It can be seen that the complex span tasks load both on the domain-general factor and the respective domain-specific storage system. These data provide an impressive degree of support for the basic structure of the working memory model.

So why is it the case that slow rates of academic learning therefore characterize children who perform poorly on complex memory measures of working memory (e.g., Pickering and Gathercole, 2004; Gathercole et al., 2006a)? We have suggested that the reason is that working memory acts as a bottleneck for learning (Gathercole, 2004; Gathercole et al., 2006b). The acquisition of knowledge and skill in complex domains such as reading and mathematics requires the gradual accumulation of knowledge over multiple learning episodes, many of which will take place in the structured learning environment of the classroom. Learning is thus an incremental process that builds upon the knowledge structures and understanding that have already been acquired: any factor that disturbs this acquisition process will have deleterious consequences for the rate of learning, as the necessary foundations for progress will not be in place. It is proposed that working memory capacity is one of the factors that constrains learning success in potential learning episodes. Many classroom activities require the child to keep information in mind while engaging in another cognitive activity that might be very demanding for that individual. Mental arithmetic is an example of such a demanding working memory activity for adults. In children, whose working memory capacity is considerably smaller and who do not have the same bedrock of stored knowledge and expertise to support cognitive processing, working memory challenges of a comparable magnitude are present in much simpler activities, such as writing sentences, adding up totals of objects displayed on cards, or detecting rhyming words in a poem read by the teacher. Children with poor working memory capacities will face severe difficulties in meeting the demands of these situations and, as a result of their working memory overload, will fail in part or all of the learning activity. Such situations represent missed learning opportunities and if they occur frequently, will result in a slow rate of learning.

2.04.2.4 The Episodic Buffer

The episodic buffer is the most recent addition to the working memory model, and was first outlined in a seminal paper by Baddeley in 2000 (Baddeley, 2000).

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In this article, Baddeley argued the need for a separate buffer capable of representing and integrating inputs from all subcomponents of working memory and from long-term memory systems in a multidimensional code.

One justification for the episodic buffer is that it solves the binding problem, which refers to the fact that although the separate elements of multimodal experiences such as seeing an object moving and hearing a sound are experienced via separate channels leading to representations in modality-specific codes, our perception is of the event as a coherent unitary whole. At some point, the representations must therefore converge and be chunked together and experienced consciously as a single object or event; Baddeley's suggestion was that the episodic buffer may fulfill this function.

Other evidence also points to a close interface between the subcomponents of working memory and other parts of the cognitive system. It has long been known that meaningful sentences are much better remembered than jumbled sequences of words, with memory spans as high as 16 words compared with the six or seven limit for unrelated words (Baddeley et al., 1987). This indicates that representations in the phonological loop are integrated at some point with conceptual representations arising from the language processing system. Importantly, patients with acquired impairments of verbal short-term memory show reduced memory span for sentences as well as for word lists, but still show the relative advantage of meaningful over the meaningless material. Patient PV, for example, had a sentence span of five and a word span of one (Vallar and Baddeley, 1984). As PV's long-term memory was entirely normal, the reduction in her sentence span must arise from the point of interaction between verbal short-term memory (or the phonological loop). Baddeley (2000) proposed that the episodic buffer may provide the appropriate medium for linking the phonological loop representations with those from long-term memory, and that the central executive may control the allocation of information from different sources into the buffer.

The characteristics of the episodic buffer have been explored in a subsequent experimental programme by Baddeley and collaborators. One line of investigation has looked into whether the episodic buffer plays a role in the binding of different visual features of objects into chunks by comparing memory for arrays of colors or shapes with memory for bound combinations of these features (Allen et al., 2006). In a series of experiments, recognition memory for visually presented objects was tested by presenting an array of objects followed by a probe; the participants' task was to judge whether the probe was present in the original display or not. Across conditions, recognition memory was tested either for shape by presenting a display of different unfilled shapes, for color with a display of squares of different colors, or for both color and shape by presenting objects composed of unique shape/color combinations. In line with previous findings from this paradigm (Wheeler and Treisman, 2002), recognition performance was found to be as accurate in the feature combination as the single feature conditions. Thus, feature binding appears to be a relatively efficient process.

Allen et al. (2006) investigated whether this binding process depends on central executive resources, as might be predicted from the working memory model shown in **Figure 1**, in which information is fed into the episodic buffer from the central executive. To test this possibility, participants also performed demanding concurrent tasks that would be expected to require executive resources – counting backwards and retaining a near-span digit load – while viewing the object arrays. The results were clear: although recognition memory was generally less accurate under dual task conditions, memory for bound features was not selectively disrupted. The only condition that did lead to a greater impairment of recognition for feature combinations than single features was one that involved sequential rather than simultaneous presentation of objects.

On the basis of these findings, Allen et al. concluded that binding the features of simple visual features takes place in the visuospatial sketchpad and does not require executive support. However, it was suggested that storage of such automatically bound information is fragile and may fall apart when further feature combinations need to be encoded and stored in visuospatial memory.

The possible role of the attentional resources of the central executive in integrating linguistic information with representations in the phonological loop in the episodic buffer was investigated by Jefferies et al. (2004). The main focus of this study was the substantial advantage found in the immediate recall of prose compared with unrelated words, which Baddeley (2000) had suggested may be mediated by the integration of linguistic and phonological information in the episodic buffer. Jefferies et al.

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conducted a series of experiments in which the relative difficulty of different kinds of lists was equated for individual participants. Thus, an example of an unrelated word list that corresponds to 50% above span for an average participant with a word span of six was the nine items essay, marmalade, is, lots, clowns, wine, spaces, often, a. In the sentence condition of a corresponding level of difficulty, an average participant with a sentence span of 13 would receive the following sequence of unrelated sentences for immediate recall: Railway stations are noisy places. Guns can cause serious injuries. Water is boiled in kettles. Pink roses are pretty flowers. In a further story condition, the sentences were thematically related, as in the following example: A teenage girl loved buying clothes. She went shopping with her mom. They traveled into town by bus.

The possible engagement of attentional processes associated with the central executive was investigated by comparing the impact of a continuous reaction time (CRT) task completed during the presentation of the memory sequence on performance in the different conditions. Following Craik et al. (1996), the CRT task involved pressing one of four keys corresponding to the spatial location of a visual target that appeared on a computer screen; as soon as the key was pressed, the next stimulus was presented. This task is known to place significant demands on controlled attentional processing. If the central executive does play a crucial role in loading phonological and linguistic information into the episodic buffer where it can be integrated into a multidimensional code underpinning sentence span, a selective decrement in the recall of sentences relative to unrelated words would be expected in the concurrent CRT conditions.

Jefferies et al. (2004) found that recall of unrelated words was more or less unaffected by the concurrent task, as was the recall of thematically organized material in the story condition. These findings indicate that the use of the phonological loop places few demands on attentional resources, and also that the activation of preexisting representations relating to the semantic and syntactic content of the stories occurs relatively automatically. In contrast, CRT did markedly impair performance in the condition involving the recall of unrelated sentences. It therefore appears that substantial attentional support from the central executive is required for the retention of unrelated chunks of linguistic information, possibly within the episodic buffer.

Although the study of the episodic buffer is still in its infancy, the concept is being refined in light of new evidence and is proving useful in guiding research on memory for relatively complex forms of material. The simple idea that the central executive is required to feed information through to the episodic buffer for the purposes of feature binding has not received strong support from the research completed so far: there is little evidence for central executive involvement in either the binding of simple visual features (Allen et al., 2006) or in the recall of coherent prose, although attentional support does appear to be crucial for the temporary retention of chunks of unrelated linguistic information (Jefferies et al., 2004). Ongoing and future research designed to delineate the precise conditions under which the central executive and episodic buffer interact seems certain to provide further fruitful insights into the role played by working memory in the storage and manipulation of complex and structured information.

2.04.2.5 Other Models of Working Memory

The multicomponent model of working memory initially advanced by Baddeley and Hitch (1974) is the most enduring and influential theoretical framework in the field. Its success rests with the breadth of scope of the model – incorporating verbal and visuospatial short-term memory, as well as attentional processes – and also with the capacity of the model to evolve in light of incoming evidence. Although the original tripartite structure of the 1974 model has been largely preserved, each component has been elaborated and differentiated over the intervening years, largely but not exclusively by using the dual task methodology to identify distinct subcomponents of the system. The model has also proved successful in accommodating evidence from a wide range of empirical traditions including cognitive development, neuropsychology, and neuroscience in addition to experimental psychology. It is, however, by no means the only model of working memory, and there are currently several other conceptualizations that are proving to be highly effective in guiding research and thinking in the area. Some of the significant alternative theoretical accounts of working are outlined in the following.

2.04.2.5.1 Attentional based models

One influential theoretical account of working memory of this type is Cowan's (1995, 2001) embedded process model, summarized in **Figure 5**. According to this model, long-term memory can be partitioned

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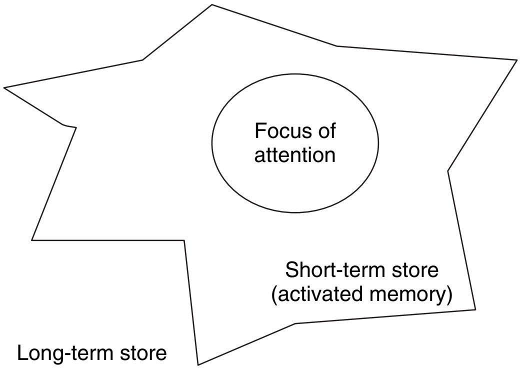

Figure 5 Cowan's (1995) embedded process model of working memory.

in three ways: the larger portion that has relatively low activation at any particular point in time, a subset that is currently activated as a consequence of ongoing cognitive activities and perceptual experience, and a smaller subset of the activated portion that is the focus of attention and conscious awareness. The focus of attention is controlled primarily by the voluntary processes of the executive system that are limited in capacity in chunks. Recent work indicates that typically between three and five chunks of information can be maintained in the focus of attention (Cowan, 2001; see also Chen and Cowan, 2005; Cowan et al., 2005). In contrast, long-term memory activation is time-limited and decays rapidly without further stimulation.

Cowan et al. (2005) have put forward an interpretation of complex memory span performance and its links with scholastic aptitude measures that is markedly divergent from the explanation based on the working memory model considered in the section titled 'The central executive.' By this account, the crucial feature of complex span tasks is that the processing activity prevents the usual deployment of control strategies such as rehearsal and grouping, and thus exposes more directly the scope of the focus of attention, as indexed by the number of chunks that can be maintained simultaneously. Learning ability will be constrained by having a relatively poor scope of attention, laid bare by complex memory span tasks.

An attentional-based account of working memory function has been also advanced by Engle and associates (e.g., Engle et al., 1999b). In some respects, Engle's model shares a similar architecture with the Baddeley and Hitch (1974) framework, combining domain-specific storage of verbal and visuospatial material with controlled attention. The detailed functioning of the components is, however, quite different. Short-term memory consists of traces that have exceeded an activation threshold and represent pointers to specific regions of long-term memory. They therefore do not represent temporary representations in a specialized temporary store, as in the phonological loop. Controlled attention is a domain-general resource that can achieve activation through controlled retrieval, maintain activation, and block interference through the inhibition of distractors.

Unsworth and Engle (2006) have recently put forward a new explanation of why complex memory span tasks correlate more highly with measures of higher-order cognitive function than simple memory span, based upon the distinction between primary and secondary memory. According to this account, memory items that have been recently encountered are held in primary memory, and may also be transferred into the more durable secondary memory system (Waugh and Norman, 1965). The processing activity in complex span tasks displaces items from primary memory, so that recall performance is supported principally by residual activation in secondary memory. Unsworth and Engle suggest that it is the ability to retrieve items from secondary memory that is crucial to more cognitive activities such as reasoning. Note that this interpretation is somewhat similar to that advanced by Cowan et al. (2005); in both cases, the claim is that learning is served most directly by the quality of activation of long-term memory, and not by the capacity of the controlled attention process that generates conscious experience.

2.04.2.5.2 The resource-sharing model

A contrasting theoretical perspective on working memory was provided by Daneman and Carpenter (1980, 1983; Just and Carpenter, 1992). These researchers conceived working memory as an undifferentiated resource that could be flexibly deployed either to support temporary storage or processing activity. By this account, individuals with relatively low span scores on complex memory span tasks were relatively unskilled at the processing element of the activity (reading, in the case of reading span), thereby reducing the amount of resource available for storage of the memory items. This idea that working memory is a single flexible system fueled by a limited capacity resource that can be flexibly allocated to support processing and storage was applied by Case et al. (1982) to explain developmental increases in working memory performance across the childhood years.

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They proposed that the total working memory resource remains constant as the child matures, but that the efficiency of processing increases, releasing additional resource to support temporary storage. Consistent with this view, Case et al. found in a study of 6- to 12-year-old children that counting spans were highly predictable from individual counting speeds. Furthermore, counting spans were reduced to the level typical of 6-year-old children when adults' counting efficiency was reduced by requiring the use of nonsense words rather than digits to count sequences. It was concluded that the decreased memory spans resulted from the greater processing demands imposed by the unfamiliar counting task, leading to a processing/storage trade-off that diminished storage capacity.

2.04.2.5.3 Time-based theories

The resource-sharing model of working memory has been challenged substantially in recent years. Towse and Hitch (1995) proposed that participants do not process and store material at the same time in complex span tasks as assumed by the resource-sharing approach, but instead strategically switch between the processing and storage elements of the task. Evidence consistent with this task-switching model has been provided in a series of studies that have either varied counting complexity while holding retention interval constant (Towse and Hitch, 1995) or manipulated retention requirements in counting, operation, and reading span tasks, while holding constant the overall processing difficulty (Towse et al., 1998). In each case, the period over which information was stored was a better predictor of complex memory span than the difficulty of the processing activity. This has led to the claim that complex memory span is constrained by a time-based loss of activation of memory items (Hitch et al., 2001).

The consensus view at present is that no single factor constrains complex memory span (Miyake and Shah, 1999; Bayliss et al., 2003; Ransdell and Hecht, 2003). A more complex model recently advanced by Barrouillet and colleagues (Barrouillet and Camos, 2001; Barrouillet et al., 2004) combines concepts of both temporal decay and processing demands in a single metric of cognitive cost that is strongly related to performance on complex span tasks. In this model, the cognitive cost of a processing task is measured as the proportion of time that it requires limited-capacity attentional resources, for example, to support memory retrievals. When attention is diverted from item storage to processing in this way, memory representations cannot be refreshed and therefore decay with time. The heaviest cognitive costs and therefore the lowest levels of complex span performance are therefore expected under conditions in which there is the greatest ratio of number of retrievals to time. Experimental findings reported by Barrouillet et al. (2004) are entirely consistent with this prediction. Using a complex memory span paradigm in which they separately manipulated the rate of presentation of the memory items and the number of intervening items to be processed, complex memory span was found to be a direct linear function of the cognitive cost of the processing activity, computed as a ratio of the number of processing items divided the period over which they were presented. Thus, processing intervals that had relatively high loads (in other words, a relatively large number of items per unit time) were associated with lower span scores than processing intervals with low cognitive loads (low numbers of items per unit time).

2.04.2.5.4 Summary

In this section, a number of alternative theoretical accounts of working memory have been considered. It can be argued that some of these conceptualizations provide valuable specifications of the nature of central executive processes and are not necessarily incompatible with the Baddeley and Hitch (1974; Baddeley, 2000) model. Certainly, the emphasis on time-based loss of information by Towse and Hitch and the ideas of Barrouillet and colleagues concerning cognitive load could readily be accommodated in an elaborated model of the central executive and its interface with the phonological loop. The majority of these alternative approaches also emphasize the role of attention in working memory, a concept given prominence also by Baddeley (1986). However, other claims that working memory is an activated subset of long-term memory and does not exist as a temporary storage medium distinct from preexisting knowledge are less easy to reconcile.

2.04.3 Overview

The ability to hold information in mind for brief periods of time, termed working memory by cognitive psychologists, is an essential feature of our everyday mental life. The purpose of this chapter is to provide a contemporary overview of current theoretical understanding of the cognitive processes

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of working memory. According to the influential model advanced originally by Baddeley and Hitch (1974) and revised and elaborated over the subsequent years (Baddeley, 1986, 2000; Burgess and Hitch, 1992, 1999), working memory consists of an attentional controller, the central executive, supplemented by slave systems specialized in the storage of verbal and nonverbal information (the phonological loop and visuospatial sketchpad, respectively). An additional component is the episodic buffer, capable of integrating information from different parts of working memory and other parts of the cognitive system. Each component of the model is limited in capacity.

This relatively simple model of working memory has proved capable of accommodating a wide range of empirical findings. Its fractionated structure has been informed by findings from experimental studies using dual task methods, by developmental dissociations in studies of children, and by evidence of distinct underlying brain from the fields of neuropsychology and neuroimaging. In the area of the phonological loop in particular, understanding of the underlying cognitive processes is sufficiently well advanced to allow the development of a computational model capable of simulating many detailed aspects of verbal short-term memory behavior.

Two components of the working memory model – the central executive and phonological loop – appear to play key roles not only in the temporary retention of information, but also in supporting longer-term learning, particularly during the childhood years. The phonological loop is important for learning the sound patterns of new words in the course of acquisition of vocabulary in native and foreign languages, whereas the central executive mediates academic learning in areas including reading and mathematics. Detailed theoretical accounts of the possible causal roles of working memory in these elements of learning are considered.

There are also several alternative theoretical accounts of working memory that are currently proving useful in guiding further research and understanding in this field. Some of these theories conceive of working memory as the subset of representations in long-term memory that have been activated either automatically via our interactions with the environment or effortfully, by being the focus of a consciously controlled attentional resource. Whereas the role played by attention is acknowledged in almost all current models of working memory, the distinction between models that assume specialized temporary storage mechanisms and those that see working memory as a property of preexisting knowledge representations is a fundamental one, yet to be resolved by empirical evidence. A further common feature of many theories is that time-based forgetting is a crucial feature of working memory.

Research in the field of working memory continues, stimulated by the availability of detailed theoretical accounts that guide empirical investigations of both typical and atypical working memory functioning. There is also increasing recognition that our current understanding of working memory can be put to more practical use, particularly in the fields of education and remediation (e.g., Gathercole and Alloway, in press). In this respect, working memory represents a strong example of how laboratory investigations of basic cognitive processes have the potential to enhance less esoteric elements of our everyday cognitive experience.

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