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Is Working Memory Still Working?*

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The current state of A.D. Baddeley and G.J. Hitch's (1974) multicomponent working memory model is reviewed. The phonological and visuospatial subsystems have been extensively investigated, leading both to challenges over interpretation of individual phenomena and to more detailed attempts to model the processes underlying the subsystems. Analysis of the controlling central executive has proved more challenging, leading to a proposed clarification in which the executive is assumed to be a limited capacity attentional system, aided by a newly postulated fourth system, the episodic buffer. Current interest focuses most strongly on the link between working memory and long-term memory and on the processes allowing the integration of information from the component subsystems. The model has proved valuable in accounting for data from a wide range of participant groups under a rich array of task conditions. Working memory does still appear to be working.

The term *working memory* appears to have been first proposed by Miller, Galanter, and Pribram (1960) in their classic book *Plans and the Structure of Behavior.* The term has subsequently been used in computational modeling approaches (Newell & Simon, 1972) and in animal learning studies, in which the participant animals are required to hold information across a number of trials within the same day (Olton, 1979). Finally, within cognitive psychology, the term has been adopted to cover the system or systems involved in the temporary maintenance and manipulation of information. Atkinson and Shiffrin (1968) applied the term to a unitary short-term store, in contrast to the proposal of Baddeley and Hitch (1974), who used it to refer to a system comprising multiple components. They emphasized the functional importance of this system, as opposed to its simple storage capacity. It is this latter concept of a multicomponent working memory that forms the focus of the discussion that follows. I myself have been using the concept for over 25 years; does it still work?

Before addressing this issue, it is perhaps appropriate to consider what are the criteria for *working.* The multicomponent model of working memory was proposed as a theoretical framework whose function was to give an economical and coherent account of a relatively wide range of data. Its success should be judged in terms of its continuing capacity to do so and to prompt new questions that in turn add to the basic understanding of cognition. To work, therefore, requires breadth of coverage coupled with a capacity to stimulate further research and to incorporate more precise quantitative and/or computational models. So, how well is working memory working?

Baddeley and Hitch (1974) proposed that the earlier unitary concept should be elaborated into a three-com-

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Figure 1
The model of working memory proposed by Baddeley and Hitch (1974).

ponent system. As Figure 1 shows, this comprises a limited capacity attentional controller, the *central executive,* aided by two subsystems, one concerned with acoustic and verbal information, the *articulatory* (subsequently *phonological)* loop, and the other performing a similar function for visual and spatial information, the *visuospatial scratchpad* (subsequently *sketchpad).** Much of the earlier work concentrated on these two subsystems, on the grounds that they appeared to offer more tractable problems than did the central executive. For that reason, they are discussed first.

The Phonological Loop

This system was proposed to give an account of the substantial evidence that had already accumulated concerning short-term verbal memory, typically involving the classic digit span procedure. The articulatory loop was assumed to comprise two components, a phonological store and an articulatory rehearsal system. Traces within the store were assumed to decay over a period of about two seconds unless refreshed by rehearsal, a process akin to subvocalization and one that is dependent on the second component, the articulatory system (Baddeley & Hitch, 1974).

The store was assumed to be reflected in the phonological similarity effect, whereby immediate serial recall of items that are similar in sound (e.g., the letters *B, V, G, T, C, D*) is poorer than that of dissimilar items (e.g., *F, K, Y, W, M, R;* Conrad & Hull, 1964). Similarity of meaning, however, typically has little effect in the standard immediate serial recall paradigm (Baddeley, 1966b). The reverse is true of the multitrial long-term learning of 10-item sequences, which appears to depend principally on semantic rather than acoustic coding (Baddeley, 1966a).

The articulatory rehearsal component was proposed to give an account of the word length effect, whereby immediate serial recall is a direct function of the length of the items being retained (Baddeley, Thomson, & Buchanan, 1975). Hence, a sequence such as *sum, pay, wit, bar, hop* is much more likely to be recalled correctly than *helicopter, university, television, alligator, opportunity.* This was originally proposed to reflect the slower rehearsal of longer words, which allows greater forgetting. It has also been claimed to result from forgetting during the process of recall, which again tends to be slower with longer words (Cowan et al., 1992; Dosher & Ma, 1998). It now appears that both of these processes are important (Baddeley, Chincotta, Stafford, & Turk, in press). Consistent with this view is the fact that when rehearsal is prevented by articulatory suppression, the repetition of an irrelevant sound such as the word *the,* the word length effect disappears (Baddeley et al., 1975).

The process of subvocal articulation also seems to play an important role in registering visually presented material within the phonological loop. Hence, articulatory suppression eliminates the effect of phonological similarity when material is presented visually but not with auditory presentation, which is assumed to provide direct access to the phonological store (Baddeley, Lewis, & Vallar, 1984; Murray, 1968). Finally, immediate serial verbal memory is impaired by the presentation of irrelevant auditory material that the participants are instructed to ignore (Colle & Welsh, 1976; Salamé & Baddeley, 1982). The disruptive effect is not limited to speech, being also found with fluctuating tones, although not when white noise varies in loudness (Jones, 1993). Precise interpretation of the irrelevant sound effect remains equivocal (Baddeley, 2000b; Jones & Tremblay, 2000; Neath, 2000).

The strength of the phonological loop model resides in the fact that it offers a simple and coherent account of a relatively complex set of data. It has, furthermore, proved readily applicable to neuropsychological deficits, notably including the case of patients who appear to have impaired short-term memory (STM), as reflected in low digit span, coupled with normal long-term memory (LTM; Shallice & Warrington, 1970; Vallar & Baddeley, 1984). Further light has been thrown on the process of subvocal rehearsal by the study of patients with different speech and language deficits. Hence, patients who have lost the peripheral control of their speech musculature are still able to rehearse (Baddeley & Wil-

* Articulatory *was changed to* phonological *to emphasize the fact that this subsystem is not limited to the articulatory component. The term* sketchpad *was adopted to emphasize that subsystem's visuospatial characteristics.*

son, 1985), whereas those who have lost the capacity to construct a speech-motor program centrally show no such capacity (Caplan & Waters, 1995). This suggests that rehearsal should be regarded as reflecting the central control of speech rather than the overt capacity to articulate. Finally, Baddeley, Gathercole, and Papagno (1998) have argued strongly that the phonological loop has evolved to support the acquisition by children of their native language and that it plays an important role in adult second-language learning.

There have, however, been challenges to virtually every aspect of the phonological loop hypothesis. For example, Neath and Nairne (1995) and Brown and Hulme (1995) have suggested that the word length effect stems from the greater fragility of multicomponent long words to the processes involved in forgetting. I myself regard this view as having difficulty in accounting for the removal of the word length effect with articulatory suppression (Baddeley et al., 1975) and with the absence of a word length effect in patients with STM deficits (Vallar & Baddeley, 1984; Vallar & Papagno, in press) and in young children who are at a stage before they begin rehearsal (see Gathercole, in press, for a review). However, the issue remains open.

The question of whether short-term forgetting represents trace decay or interference, a classic issue of the 1960s, remains unresolved. The trace decay assumption was adopted on the basis of rather slender evidence, together with its greater simplicity. An interference theory interpretation invites a much tighter specification than my colleagues and I have felt able to achieve. For example, should it follow the classic stimulus-response associationist principles, as Melton (1962) proposed, or should it be closer to the Waugh and Norman (1965) concept of interference resulting from subsequent items displacing earlier traces within a limited capacity system? Indeed, even trace decay could be seen as a form of interference; given that the nervous system appears to be continuously active, a greater delay will involve more subsequent neural activity leading to a greater potential disruption of the memory trace. Testing any of these is likely to demand a more precise specification of the phonological loop than Baddeley and Hitch (1974) were able to offer.

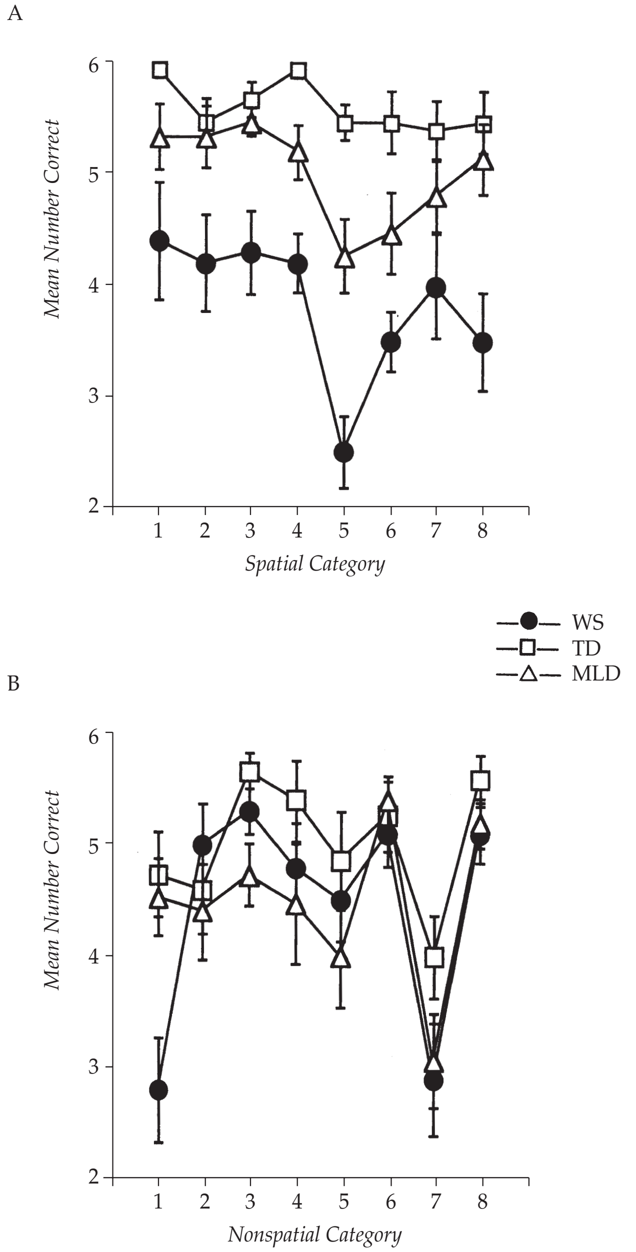
One aspect of this lack of specificity is particularly important, namely, the failure of the model to give any account of how the serial order of the incoming items is maintained. Although simple chaining models are common within the literature (Murdock, 1993; Wickelgren, 1966), chaining is inconsistent with the pattern of errors observed when participants attempt to remember sequences comprising alternate similar and dissimilar items (e.g., *B, W, T, R, P, X*), where errors fall on the similar items rather than on the dissimilar letters following them (Baddeley, 1968; Henson, Norris, Page, & Baddeley, 1996). This result has led to a range of computational and mathematical models attempting to specify in considerable detail the processes involved in phonological STM. Some fit readily within the phonological loop framework (Burgess & Hitch, 1992, 1999; Henson, 1998; Page & Norris, 1998), whereas other approaches differ in important ways from the phonological loop model (Brown & Hulme, 1995; Nairne, 1990; Neath, 2000). Although it is certainly too soon to draw any firm conclusions, it is clear that the phonological loop model is capable of more detailed computational specification and that this represents an important route for future development of the model.

Before moving on from the phonological loop, two further developments should be discussed. The first of these concerns the interaction between the phonological loop and LTM. Baddeley, Gathercole, and Papagno (1998) proposed that an important evolutionary function of the loop is to facilitate the acquisition of language by maintaining the representation of a new word so as to optimize learning. Evidence for this comes from the impairment of foreign language acquisition in patients with a classical STM deficit (Baddeley, Papagno, & Vallar, 1988) and also from normal children, for whom the capacity to hear and repeat back an unfamiliar pseudoword (nonword repetition) predicts level of vocabulary development (Gathercole & Baddeley, 1989). Children with a specific language impairment (SLI) are found to be particularly impaired on nonword repetition. Hence, eight-year-olds with normal nonverbal intelligence, coupled with the verbal development of six-year-olds, showed a level of nonword repetition that was equivalent to that of four-year-olds (Gathercole & Baddeley, 1990). Bishop, North, and Donlan (1996), carrying out a twin study, found nonword repetition to be strongly associated with SLI and to have very high heritability. The precise mechanism whereby impaired phonological loop capacity results in poor language development is discussed elsewhere (Baddeley, in press; Baddeley, Gathercole, & Papagno, 1998) but remains an area of considerable current theoretical and empirical activity (Gathercole, 1996).

I should finally address one broad issue, namely, that of whether it is necessary to assume a separate phonological store rather than propose that the phenomena described represent the temporary activation of structures within LTM. Such a view is adopted, for example, by Cowan (2001), whose views otherwise do not differ markedly from my own (Baddeley, 2001). I myself reject this view for two reasons. First, I reject this view because LTM activation appears to provide an explanation without in fact doing so, unless it specifies the way in which the many different features of working memory can be mapped onto mechanisms within the LTM system. The second reason stems from the detailed analysis of the evidence, particularly that of neuropsychological patients, whose marked phonological STM deficits can occur with apparently normal language and verbal LTM (Vallar & Baddeley, 1984). Both phonological STM and visuospatial STM also appear to be associated with specific brain locations on the basis of evidence from both lesion and functional imaging studies using both positron emission tomography and functional magnetic resonance imaging (fMRI; see Della Sala & Logie, in press; Smith & Jonides, 1996; and Vallar & Papagno, in press, for reviews). I therefore continue to hold the position that the phonological loop represents an active system for temporary storage that has evolved on the grounds of its functional value. Although it draws on processes that initially developed for speech perception and production, it represents a separate system. A recent and careful review of this whole issue is provided by Margaret Wilson (2001).

The Visuospatial Sketchpad

This system is assumed to be capable of temporarily maintaining and manipulating visuospatial information, playing an important role in spatial orientation and in the solution of visuospatial problems. A good overview is provided by Logie (1995), and an account of neuropsychological deficits within this system is given by Della Sala and Logie (in press). The sketchpad is assumed to form an interface between visual and spatial information, accessed either through the senses or from LTM. As such, it allows a range of channels of visual information to be bound together with similar information of a motor, tactile, or haptic nature. A good deal of research over recent years has been concerned with establishing the potential separability of its visual and its spatial components. Although it is difficult to provide tasks that reflect one or other component in a pure form, there is both behavioral and neuropsychological evidence to suggest an association between spatial STM and the Corsi block-tapping task, in which the participant attempts to copy a sequence of movements made by the experimenter in tapping an array of blocks. The visual component is reflected more strongly in pattern



Note. Williams syndrome is associated with impaired spatial working memory. As Figure 2 shows, it is also associated with difficulty in processing spatially based syntax, as compared with typically developing normal children or with people with minimal learning disability. The difference is not present for nonspatial syntactic forms (Figure 2B). Data are from "Spatial Language Difficulties in Williams Syndrome: Evidence for Use of Mental Models?" by C. Phillips, C. Jarrold, A.D. Baddeley, J. Grant, and A. Karmiloff-Smith, 2001, manuscript submitted for publication.

Figure 2
Processing of spatial and nonspatial syntactic forms by groups with Williams Syndrome (WS) and minimal learning disability (MLD) and by typically developing (TD) children. © 2001 by A.D. Baddeley, University of Bristol, UK.

span. This involves showing the participant a matrix in which half of the cells are filled and requiring immediate recall or recognition; the size of the matrix is increased to visual span, at which errors begin to occur (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999).

The sketchpad can be disrupted by requiring participants to tap repeatedly a specified pattern of keys or locations, a procedure that impairs the use of visuospatial imagery (Baddeley & Lieberman, 1980). Unattended patterns or visual noise may disrupt the visual component of the system (Logie, 1986; Quinn & McConnell, 1996).

A role for the sketchpad in sentence processing is indicated by recent work involving people with Williams syndrome (Phillips, Jarrold, Baddeley, Grant, & Karmiloff-Smith, 2001), a genetically based learning disability characterized by relatively preserved language and verbal STM, together with impaired spatial processing and Corsi tapping span (Bellugi, Wang, & Jernigan, 1994; Jarrold, Baddeley, & Hewes, 1999). As Figure 2 indicates, this verbal-spatial dissociation extends to sentence verification; people with Williams syndrome show a specific deficit in processing sentences involving spatial syntactic forms, such as *above* and *below* or *inside* and *outside* (Figure 2A), as compared with nonspatial forms such as negatives and reversible passives. The aberrant point (1) on Figure 2B involves the lighter-darker distinction that was assumed to be visual but nonspatial.

A challenging issue within this area concerns the nature of visuospatial rehearsal. Logie (1995) regarded the spatial component of the system, which he termed the *inner scribe,* as the basic mechanism for rehearsal. My own tentatively held current view is that a process analogous to attention is capable of maintaining activity through the operation of the central executive. I now regard this as a more typical mechanism for maintenance rehearsal than the subvocal rehearsal component of the phonological loop. I regard this as a special case that stems from human verbal capacity to reproduce incoming verbal material accurately and, with familiar forms such as digits and words, to correct errors on the basis of prior knowledge.

Both neuropsychological evidence and functional imaging evidence support the view of the sketchpad as a multicomponent system, with occipital lobe activation presumably reflecting the visual pattern component, parietal regions representing spatial aspects, and frontal activation responsible for coordination and control (Smith & Jonides, 1996). Separating the subcomponents of the sketchpad has proved more difficult than dissecting the phonological loop (Della Sala & Logie, in press). However, one feature suggests that future developments may be more rapid. Single-unit recording studies in awake monkeys have allowed the tracing of an active short-term visual memory system that would appear to have considerable similarity to the visuospatial sketchpad and its control processes in humans (Goldman-Rakic, 1996). At the same time, the study of visual attentional processes would appear to provide an extremely promising bridge between work on monkeys and work on the visuospatial sketchpad (Humphreys, Duncan, & Treisman, 1998).

The Central Executive

The third component of the working memory framework, the central executive, was initially conceived in the vaguest possible terms as a limited capacity pool of general processing resources. For the first decade, it served principally as a convenient ragbag into which could be thrust such awkward questions as what determined when the sketchpad or phonological loop was used and how they were combined. Implicitly, the central executive functioned as a homunculus, a little man who took the important decisions as to how the two slave systems should be used. Although this might seem to be a somewhat cowardly approach to theory, it is to some extent inevitable. All theories delimit their range either implicitly or explicitly. If this were not the case, then interpretation of every experiment, whatever its function, would also require the theorist to give an account of the way in which the instructions had been understood, the strategy selected, and, indeed, what motivated the participants. A good experimenter will, of course, be fully aware of these as important variables but very reasonably not expect to incorporate them explicitly in his or her explanation.

However, the central executive does play a crucial role in the working memory framework and, as such, demands explanation if not immediately, then as part of a more complete theory. The executive may still resemble a homunculus, but this is no bad thing as long as it is accepted that the role of a homunculus is to remind researchers of those functions that they have not yet explained (Attneave, 1960). It demands a strategy of systematically attempting to specify these processes and explain them, hopefully in due course leaving nothing further to explain, hence allowing the homunculus to retire. My colleagues and I adopted this strategy, concentrating on the attentional control characteristics of the central executive and borrowing what was virtually the only model attempting to explain the attentional control of action at that time, namely, the supervisory attentional subsystem (SAS) model of Norman and Shallice (1986).

The SAS model was developed to account for two broad types of data, absentmindedness in normal participants (Reason, 1984) and the disturbance of attentional control that frequently accompanies damage to the frontal lobes of the brain (Shallice, 1982). Human action is assumed to be controlled principally by an extensive series of schemata and habits that are able to use environmental cues to allow the performance of routine tasks such as driving a car through a busy city to a familiar location. Although this frequently leads to conflicts between different cues, for example, that of continuing driving to the intended goal versus stopping at a red traffic light, it is assumed that a number of relatively automatic conflict-resolution processes exist, of the type typically specified in production system models (Newell & Simon, 1972). The SAS is necessary when a new problem occurs, for example, when driving to an unfamiliar location or dealing with a flat tire. The attentionally limited SAS is capable of combining information from LTM with existing stimuli to plan a novel solution and to ensure that the plan is followed. Slips of action occur when the SAS fails to override a habit, such as driving to one's office when intending to go to the supermarket. Patients with frontal lobe damage show attentional problems such as perseverating on a given act because an impaired SAS has led to action being captured by the immediate environmental stimuli (Shallice, 1982).

Having provisionally accepted this existing interpretation of the executive, my colleagues and I then began to explore its potential subprocesses. The first of these was the capacity to focus attention, given the further assumption that anything that limited attentional capacity would impair performance. In one study (Robbins et al., 1996), my colleagues and I examined the effect of tasks that were intended to disrupt the phonological loop, the visuospatial sketchpad, and the central executive on chess, an activity that seemed likely to place heavy demands on the central executive. The performance of novices and experts was compared. Articulatory suppression had no impact on performance, suggesting no role for verbal working memory. Participants were, however, disrupted by a concurrent visuospatial task and even more impaired by the task of generating random digits, which is assumed to place a heavy load on the central executive (Baddeley, Emslie, Kolodny, & Duncan, 1998). Performance of both experts and novices differed in overall level but showed the same pattern of sensitivity to visuospatial and central executive disruption, both for remembering a chess position and for choosing the best next move.

One does not find this pattern in all complex tasks, however. Retrieval from LTM, for example, does not appear to depend heavily on the executive. In a series of experiments, my colleagues and I imposed a demanding secondary task during the process of learning and/or retrieving lists of words (Baddeley, Lewis, Eldridge, & Thomson, 1984). Although concurrent load had a clear effect on learning, it had little influence on recall accuracy. Craik and colleagues have subsequently replicated this and have revealed the further interesting feature that, despite being itself unaffected, retrieval does disrupt the performance of the secondary task, although the degree of impairment is not sensitive to the level of secondary task demand (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). In conclusion, the capacity to focus available attentional capacity is clearly an important feature of the executive. It is, however, important to acknowledge that not all tasks, or indeed all complex tasks, are heavily dependent on this capacity.

A second attentional process attributed to the central executive is that of dividing attention (Baddeley, 1996). Much of my work in this area has focused on patients with Alzheimer's disease (AD), who, in addition to their marked impairment in episodic LTM, show attentional deficits (Perry & Hodges, 1999). This work of my colleagues and myself stemmed from a suggestion that AD patients may have central executive impairment, resulting in the development of a task that would appear to depend on the central executive (Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991). Patients were required to combine tasks depending principally on the phonological loop (digit span) and on the visuospatial sketchpad (pursuit tracking). In each case, level of performance on the individual tests performed alone was titrated to a point at which accuracy was equivalent for AD patients and for both elderly and young control participants. However, when performed simultaneously, dual-task performance was dramatically impaired by AD but was not affected by age. When the two tasks were performed alone, however, there was no evidence that increasing level of difficulty differentially affected the AD patients (Logie, Della Sala, Wynn, & Baddeley, 2000). These and other studies using both AD patients and normal participants appear to argue for a separable executive capacity to divide attention (Baddeley, Baddeley, Bucks, & Wilcock, 2001; Bourke, Duncan, & Nimmo-Smith, 1996; Perry & Hodges, 1999).

A third potential executive capacity is that of switching attention, something that is said to be particularly susceptible to frontal lobe damage (Shallice, 1988). After pioneering work by Jersild (1927) and Spector and Biederman, (1976), the topic was largely neglected until revived by an influential paper by Allport, Styles, and Hsieh (1994), whose work suggested that the capacity to switch attention is by no means necessarily one that depends strongly on executive capacity. Indeed, our own recent work (Baddeley, Chincotta, & Adlam, in press), although indicating some contribution from the executive, has implicated the phonological loop much more strongly, at least in the task that was selected. This result has had the positive effect of alerting my colleagues and me to the potential importance of the phonological loop in controlling action, a point emphasized by the classic work of Vygotsky (1962) and Luria (1959) and more recently raised by Miyake and Shah (1999). The question of whether task switching should be regarded as an executive process, or perhaps a range of processes, remains to be decided (see Monsell & Driver, 1999).

The Episodic Buffer

A fourth role suggested for the central executive is that of forming an interface between the subsystems and LTM (Baddeley, 1996). This problem has been largely ignored by the model. It is reflected very clearly in the contrast between immediate memory for prose and for unrelated words, with word span typically being about 5 items, whereas sentence span may be as high as 16 words (Baddeley, Vallar, & Wilson, 1987). The simple assumption would be to suggest that the other 10 or 11 words come from LTM, in which case a patient with a very specific STM deficit should have a sentence span of around 10. In fact, it is about 5 (Vallar & Baddeley, 1984). It is also the case that immediate memory is sensitive to semantic similarity, provided the material is meaningful (Baddeley, in press; Baddeley & Levy, 1971), and that even span for unrelated words is susceptible to variables such as word frequency and imageability, which are presumed to represent LTM rather than the phonological loop (Hulme, Roodenrys, Brown, & Mercer, 1995).

Also problematic for the model is the recall of prose paragraphs. Although brain-damaged patients typically do poorly on both immediate and delayed recall of prose passages, a few patients appear to show excellent immediate recall despite dense amnesia that reduces delayed recall to zero. Such patients typically have well-preserved intelligence and central executive capacity (Baddeley & Wilson, in press). Within the tripartite model, however, it is difficult to provide a convincing account, given the limited capacity of the subsystems and the assumption that the central executive is a purely attentional system without its own storage capacity (Baddeley, 1996; Baddeley & Logie, 1999). Prose recall typically reflects the process of *chunk*ing, whereby recall is enhanced by aggregating items into larger units—words into phrases, for example—hence allowing more economical storage (Miller, 1956; Miller & Selfridge, 1950). Despite its generality and importance, the tripartite working memory model provides no adequate explanation of chunking. The capacity of densely amnesic patients to remember complex material is not limited to prose recall. E. Tulving (personal communication, 1999) described a densely amnesic patient who remains an excellent bridge player, able not only to remember the contract bid but also to keep track of which cards have been played during a game well enough to win the rubber.

Another problem for the tripartite model is that of how information from the two subsidiary systems could be bound together. Even simple verbal span shows evidence of combined verbal and visual encoding (Chincotta, Underwood, Abd Ghani, Papadopoulou, & Wresinksi, 1999; Logie et al., 2000). If the two stores are separate, how and where is the information combined? Is there perhaps, at some level, a common code?

A similar problem is raised by a recent attempt to use the working memory model to address the question of conscious awareness (Baddeley & Andrade, 2000). Although my colleagues and I had implicitly assumed that the sketchpad was the basis for visual imagery and the phonological loop for auditory, an attempt to spell this out made it clear that there was no direct evidence (Baddeley & Logie, 1992). My colleagues and I therefore decided to tackle this question by asking participants to form images and then judge their vividness, at the same time as performing tasks that were assumed to disrupt each of the two subsidiary systems proposed as components of working memory. When participants were forming an image of a novel visual or auditory array that they had just experienced, there was good support for the role of the two subsystems; articulatory suppression reduced the rated vividness of auditory images and spatial suppression that of visual. However, when participants were asked to form images from their long-term knowledge, for example, a local market scene or the sound of a telephone conversation, the pattern changed. The subsidiary systems still played a significant role, but

LTM factors became much more important, with rated vividness depending on factors such as whether the scene was active or passive and conventional or bizarre. Vividness appeared to depend on the amount of quasi-sensory knowledge available, whether based on LTM or STM (Baddeley & Andrade, 2000). My colleague and I drew a number of conclusions, including: (a) Participants were able to make judgments of vividness readily and apparently meaningfully, (b) such judgments reflect a combination of working memory and LTM factors, and (c) the current model is incapable of capturing the mode by which such information is combined. We also concluded that this process could not simply reflect a look-up in LTM, given that human beings are apparently able to combine images in a novel way to create, for example, an image of a swan shopping or of an ice-hockey-playing elephant, combinations that were unlikely to have been encountered previously.

Finally, the earlier abandonment of the assumption that the executive has storage capacity, left the model with no ready explanation of work on individual differences in working memory that has been the most prominent feature in research on the topic in North America. Daneman and Carpenter (1980, 1983), adopting the broad assumption that working memory involves the capacity simultaneously to process and store information, devised a technique they termed *working memory span.* Participants are required to read and/or verify a sequence of sentences, storing the last word of each, which they then must subsequently recall. They showed that performance on this task correlates with reading comprehension, a finding that has been replicated across many subsequent studies (Daneman & Merikle, 1996). Further research has shown sentence span to be associated with performance on tasks ranging from semantic category generation to speed in acquiring programming or electronics skills (see Engle, 1996, for a review). Kyllonen and Christal (1990) have suggested that working memory span is virtually equivalent to a measure of general intelligence and that it further has the advantage of being testable using material that is less influenced by earlier academic experience than the type of reasoning task that is often used in intelligence testing. However, although working memory span has proved to be a valuable tool, there has until recently been surprisingly little attempt to examine its constituent processes.

One exception to this neglect is the work by Engle and his colleagues, who have typically attempted to provide an explanation in terms of a single overall capacity, such as the capacity for inhibition (Conway & Engle, 1994; Engle, 1996). An important feature of Engle's work has been the demonstration that high- and low-span participants appear to use different strategies, casting serious doubt on the wisdom of regarding working memory span as a continuous measure (Conway & Engle, 1994). The measure has also been questioned by neuropsychological evidence suggesting that it probably reflects the operation of a number of subcomponents rather than a single pool of processing or inhibitory capacity (Waters & Caplan, 1996). There is, however, no doubt that, whatever its interpretation, working memory span captures an important cognitive capacity. Once again, however, it is unclear how its findings could be related to the multicomponent model of working memory.

The problems I have described for the working memory model all stem from the need to integrate information from the subsidiary systems and from LTM in a way that allows active maintenance and manipulation. To solve this problem, a fourth component was proposed, the *episodic buffer* (Baddeley, 2000a, 2001, in press). The episodic buffer is assumed to represent a storage system using a multimodal code. It is assumed to be episodic in the sense that it holds integrated episodes or scenes and to be a buffer in providing a limited capacity interface between systems using different codes. It fulfills some of the functions implicitly assigned by Baddeley and Hitch (1974) to the executive. However, the executive is now assumed to be a purely attentional system whose role extends beyond memory function (Baddeley & Logie, 1999), whereas the episodic buffer is assumed to be purely mnemonic in character. It is proposed that retrieval from the buffer is through conscious awareness, with the buffer serving the binding function that is assumed to be the principal biological advantage of consciousness. This allows multiple sources of information to be considered simultaneously, creating a model of the environment that may be manipulated to solve problems and plan future behavior (Johnson-Laird, 1983).

How would the episodic buffer concept account for the problematic data described above? Its account of prose recall is not dissimilar to the concept of long-term working memory proposed by Ericsson and Kintsch (1995). Comprehending a complex passage is assumed to require the activation of representations in LTM, in a way already assumed by the working memory account of the recency effect (Baddeley & Hitch, 1993), together with the integration of such representations into a novel episodic structure, using LTM to facilitate chunking (Miller, 1956). It is assumed that this structure is held within the buffer and maintained using attentionally limited executive processes. This normally leads to the registration and consolidation of this novel representa-

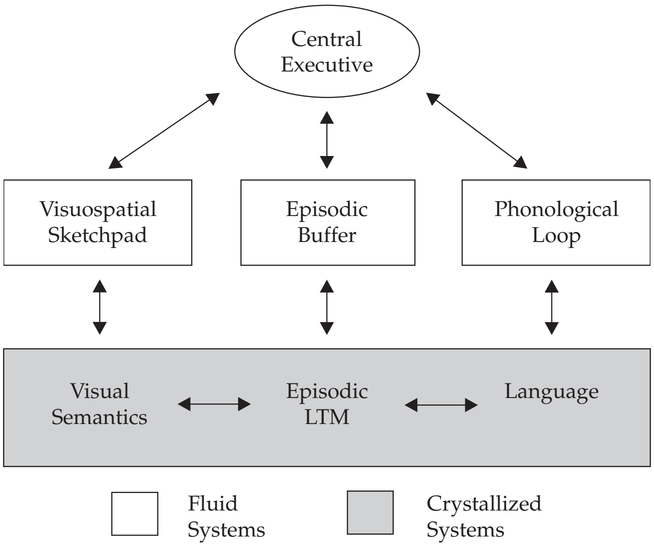


Figure 3
The current model of working memory, revised to incorporate links with long-term memory (LTM) by way of both the subsystems and the newly proposed episodic buffer (Baddeley, 2000a).

tion in LTM. In densely amnesic patients, however, such learning does not occur, with the result that once executive processing is directed elsewhere, the structure dissolves and is forgotten. The capacity for temporarily maintaining such structures reflects the capacity not only of the buffer itself but also of the subsystems and the central executive. Preservation of all three within amnesic patients is rare but does occasionally occur, resulting in preserved immediate prose recall coupled with little recall after a delay (Baddeley & Wilson, in press). Within normal participants, my colleagues and I have suggested that the capacity of this complex system is reflected in working memory span.

The revised multicomponent model is shown in Figure 3. It differs from the initial model in two important ways.

First of all, an explicit link is proposed between the two subsidiary systems and verbal and visual LTM. Although the evidence for this comes principally from the verbal domain (Baddeley, Gathercole, & Papagno, 1998), it seems probable that equivalent visuospatial linking processes exist. These presumably result in the gradual accumulation of nonverbal semantic information, such as the typical colors of objects or how certain animals or people move, together with implicit knowledge of the physical and mechanical world. The flow of information is assumed to be bidirectional; the subsidiary systems feed the relevant areas of LTM but are themselves assisted by implicit knowledge of language and of the visuospatial world, making wordlike nonwords and patterns that resemble real objects easier to recall.

The second major change within the model is, of course, the episodic buffer. This is assumed to be capable of combining information from LTM with that from the slave systems. The lack of arrows within the model directly linking the subsystems and the buffer represents an initial hypothesis that such transformations depend critically on the central executive. My colleagues and I propose to test this, and in due course, arrows may appear.

Addition of a fourth component after 25 years clearly raises a number of issues. How does the model now differ from others in the literature? Is it neuropsychologically plausible? Most important of all, how might it be tested? Space forbids a detailed discussion of these points (see Baddeley, 2000a), but possible answers to the questions are as follows.

The model differs from Tulving's concept of episodic memory in postulating a structure concerned with temporary storage, albeit one that is intimately connected to episodic LTM. It also differs from Ericsson and Kintsch's (1995) long-term working memory in postulating a separate short-term system over and above that of activated LTM and in tying this system explicitly to the earlier tripartite model. This also represents the principal difference from Cowan's views (Baddeley, 2001; Cowan, 2001).

How might the model be instantiated at a neuropsychological level? First, it seems unlikely that it occupies a single anatomical location, although the frontal lobes seem likely to play an important role in the coordinating function. Indeed, Prabhakaran, Narayanan, Zhao, and Gabrielli (2000), on the basis of an fMRI study, have explicitly concluded that "the present fMRI results provide evidence for another buffer, namely one that allows for temporary retention of integrated information" (p. 89), with the activation responsible being principally frontally located. This is clearly an interesting line to follow.

My colleagues and I are already attempting to explore the concept of an episodic buffer at an experimental level, initially by developing a measure of its capacity. The first attempt involves a measure termed *constrained sentence* span. The aim is to produce a span measure in which performance can be enhanced by combining verbal, semantic, and visuospatial information. By having sentences of a constant syntactic structure that increase in length while repeatedly using words from a limited set, as in classic span measures, the hope is to minimize any contribution from the passive priming of representations in LTM. The sentences are all of the same subject-verb-object form, with longer sentences being produced by the addition of adjectives and adverbs. Hence, a four-word sentence (excluding function words) would be *Peter cleaned the new car,* and its eight-word equivalent would be *John the angry lawyer instantly borrowed the red book from Lucy.*

Initial studies suggest that participants do indeed differ in span measured under these conditions, typically ranging between 5 and 10 words, and that the measure is relatively stable across a number of test trials (Baddeley & Turk, 2001). When participants were required to recall span-length sentences or word lists while performing concurrent tasks designed to disrupt the phonological loop, the sketchpad, or the executive, constrained sentence span proved most sensitive to concurrent visuospatial and particularly central executive tasks, whereas unrelated word recall was strongly affected by articulatory suppression, suggesting that executive processes are less important in this task. This is, of course, simply the beginning of what is likely to be a long road. My colleagues and I hope, however, that this measure or one of its successors will prove as good an individual difference measure as working memory span, while allowing better control of the material and a more detailed analysis of the underlying processes. I trust that this will be one of a range of approaches to the analysis of the capacity of working memory to integrate information from many sources and to use this integrated representation to plan and control future action.

Conclusion

The multicomponent approach to working memory aims to understand the way in which information is temporarily stored and maintained in the performance of complex cognitive processing. Although its emphasis on structures rather than processing has not always met with approval, it has for many years formed a productive basis for the systematic accumulation of knowledge about important cognitive capacities. Given that I believe this to be one of the most important functions of a theory, I would suggest that working memory has worked and is still working.

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