The episodic buffer: a new component of working memory?

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In 1974, Baddeley and Hitch proposed a three-component model of working memory. Over the years, this has been successful in giving an integrated account not only of data from normal adults, but also neuropsychological, developmental and neuroimaging data. There are, however, a number of phenomena that are not readily captured by the original model. These are outlined here and a fourth component to the model, the episodic buffer, is proposed. It comprises a limited capacity system that provides temporary storage of information held in a multimodal code, which is capable of binding information from the subsidiary systems, and from long-term memory, into a unitary episodic representation. Conscious awareness is assumed to be the principal mode of retrieval from the buffer. The revised model differs from the old principally in focussing attention on the processes of integrating information, rather than on the isolation of the subsystems. In doing so, it provides a better basis for tackling the more complex aspects of executive control in working memory.

Theoretical structures within cognitive science come in different forms, ranging from detailed mathematical or computational models of narrow and precisely defined phenomena, to broad theoretical frameworks that attempt to make sense of a wide range of phenomena and that leave open much of the more detailed specification. The purpose of such a framework is to represent what is currently known while at the same time prompting further questions that are tractable. This is likely either to extend the range of applicability of the model, or to increase its theoretical depth, subsequently leading to more precisely specified sub-models. The concept of working memory proposed by Baddeley and Hitch[1] provided such a framework for conceptualizing the role of temporary information storage in the performance of a wide range of complex cognitive tasks (see Box 1). It represented a development of earlier models of short-term memory, such as those of Broadbent[2], and Atkinson and Shiffrin[3], but differed in two ways. First it abandoned the concept of a unitary store in favour of a multicomponent system, and second it emphasized the function of such a system in complex cognition, rather than memory *per se.*

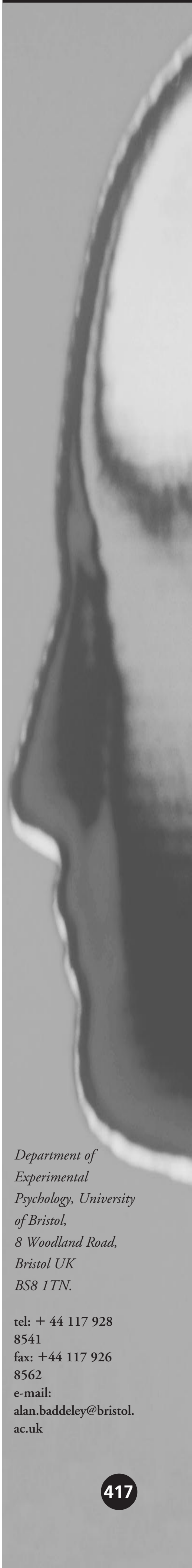
Over the 25 years since the publication of our initial paper, the concept of working memory (WM) has proved to be surprisingly durable. In one form or another, it continues to be actively used within many areas of cognitive science, including mainstream cognitive psychology[4], neuropsychology[5], neuroimaging[6], developmental psychology[7] and computational modelling[8,9]. However, there have always been phenomena that did not fit comfortably within the Baddeley and Hitch model, particularly in its more recent form. An attempt to come to terms with these has led to a reformulation of the theoretical framework, which will be described below. The reformulation leads to the proposal of a new component of working memory, the 'episodic buffer'.

Problems for the current model

The phonological loop: limits and limitations

The phonological loop gives a reasonably good account of a wide range of data (see Box 2). There are, however, phenomena that do not seem to fit neatly into the picture without serious further modification. Consider, first, the effect of articulatory suppression, whereby the subject continues to utter an irrelevant word such as 'the', while attempting to remember and repeat back a visually presented sequence of numbers. According to the model, suppression should prevent the registration of visual material in the phonological loop, producing a devastating impact on subsequent recall. Suppression does have a significant effect, but by no means devastating; in a typical study, auditory memory span might drop from 7 to 5 digits[10] . Furthermore, patients with grossly impaired short-term phonological memory, resulting in an auditory memory span of only one digit, can typically recall about four digits with visual presentation[11]. How are such digits stored?

An obvious possibility is in terms of the visuospatial sketchpad. However, the evidence indicates that this system is good at storing a single complex pattern, but not suited to serial recall[12]. Furthermore, if visual coding were involved then one might expect suppression to make recall performance very sensitive to effects of visual similarity. A recent study by Logie *et al.* does indeed show visual similarity effects[13]. They are, however, small and not limited to conditions of articulatory suppression.



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Box 1. The concept of working memory

The term working memory is used in at least three different ways in different areas of cognitive science. It is used here, and in cognitive psychology generally to refer to a limited capacity system allowing the temporary storage and manipulation of information necessary for such complex tasks as comprehension, learning and reasoning (Refs a,b). In the animal learning laboratory the term refers to the storage of information across several trials performed within the same day, as demanded by tasks such as the radial arm maze (Ref. c). In artificial intelligence, production system architectures apply the term to the component, often unlimited in capacity, that is assumed to be responsible for holding the productions (Ref. d).

These three meanings are thus not interchangeable. Performance of rats on a the radial arm maze, for example, probably relies upon long-term memory (LTM), while the unlimited capacity of the working memory component typically assumed by production system architectures differs markedly from the capacity limitation assumed by most of the models proposed within cognitive psychology.

The multi-component model of working memory (WM) that forms the basis of this review developed from an earlier concept of short-term memory (STM), that was assumed to comprise a unitary temporary storage system. This approach was typified by the model of Atkinson and Shiffrin (Ref. e). However, their model encountered problems (1) in accounting for the relationship between type of encoding and LTM (Ref. f), (2) in explaining why patients with grossly defective STM had apparently normal LTM, and (3) in accounting for the effects of a range of concurrent tasks on learning, comprehending and reasoning (Ref. b).

Baddeley and Hitch proposed the three-component WM model (shown in Fig. Ia) to account for this pattern of data. The model comprised an attentional control system, the 'central executive', aided by two subsidiary slave systems, the 'phonological loop' and the 'visuospatial sketchpad' (Ref. b). The loop is assumed to hold verbal and acoustic information using a temporary store and an articulatory rehearsal system, which clinical lesion studies, and subsequently neuroradiological studies, suggested are principally associated with Brodmann areas, 40 and 44 respectively. The sketchpad is assumed to hold visuospatial information, to be fractionable into separate visual, spatial and possibly kinaesthetic components, and to be principally represented within the right hemisphere (areas 6, 19, 40 and 47). The central executive is also assumed to be fractionable. Although it is less well understood, frontal lobe areas appear to be strongly implicated. An excellent recent overview of short-term and working memory is given by Gathercole (Ref. g).

Working memory and long-term memory were initially treated as quite separate because patients with clear short-term phonological deficits appear to have intact LTM (Ref. b). Subsequent research has shown that such patients do have specific deficits in long-term phonological learning, for example, learning the vocabulary of a new language (Ref. h). Further evidence based on the link between phonological loop performance and vocabulary level in children, suggests that the loop might have evolved to enhance language acquisition (Ref. h). As predicted by this supposition, patients with phonological loop deficits have great difficulty in acquiring novel vocabulary. It seems likely that a similar function is served by the visuospatial sketchpad, although there is as yet little investigation of this topic. If one accepts the hypothesis of an equivalent function for the sketchpad, possibly in acquiring visuospatial semantics, then the framework is modified to that shown in Fig. Ib.

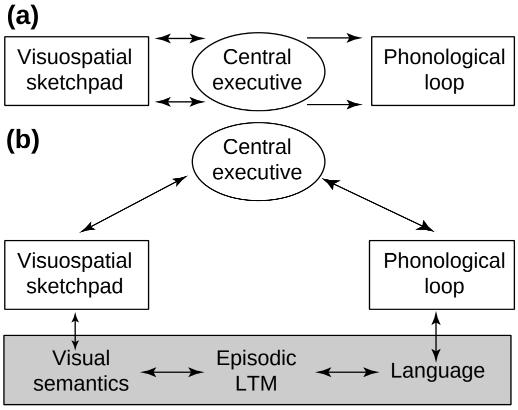

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Fig. I. (a) The initial three-component model of working memory proposed by Baddeley and Hitch (Ref. b). The three-component model assumes an attentional controller, the central executive, aided by two subsidiary systems, the phonological loop, capable of holding speech-based information, and the visuospatial sketchpad, which performs a similar function for visual information. The two subsidiary systems themselves form active stores that are capable of combining information from sensory input, and from the central executive. Hence a memory trace in the phonological store might stem either from a direct auditory input, or from the subvocal articulation of a visually presented item such as a letter. **(b) A further development of the WM model.** It became clear that the phonological loop plays an important role in long-term phonological learning, in addition to short-term storage. As such it is associated with the development of vocabulary in children, and with the speed of acquisition of foreign language vocabulary in adults. The shaded areas represent 'crystallized' cognitive systems capable of accumulating long-term knowledge (e.g. language and semantic knowledge). Unshaded systems are assumed to be 'fluid' capacities, such as attention and temporary storage, and are themselves unchanged by learning, other than indirectly via the crystallized systems (Ref. i).

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This effect of visual similarity on span for verbal materials presents something of a problem; given that it occurs under standard non-suppressed conditions, it indicates that visual and phonological information are combined in some way. The

Box 2. The phonological loop

The phonological loop is probably the best developed component of the working memory model. It is assumed to comprise a temporary phonological store in which auditory memory traces decay over a period of a few seconds, unless revived by articulatory rehearsal. The loop is assumed to have developed on the basis of processes initially evolved for speech perception (the phonological store) and production (the articulatory rehearsal component). It is particularly suited to the retention of sequential information, and its function is reflected most clearly in the memory span task, whereby a sequence of items such as digits must be repeated back immediately in the order of presentation. Digit span, the maximum number of digits that can be retained perfectly on 50% of occasions (typically about seven), is assumed to be determined jointly by the durability of the memory trace, and the time required to refresh the trace by subvocal rehearsal.

This model gives a simple account of the following phenomena:

(1) The phonological similarity effect
Items such as letters or words that are similar in sound are harder to remember accurately (e.g. the sequence *g, c, b, t, v, p* is harder than *f, w, k, s, y, q*), whereas visual or semantic similarity has little effect (Refs a,b). This implies an acoustic or phonological code.

(2) The word-length effect
Subjects find it easier to recall a sequence of short words (e.g. *wit*, *sum*, *harm*, *bag*, *top*) than long words (*university*, *aluminium*, *opportunity*, *constitutional*, *auditorium*). It takes longer to rehearse the polysyllables, and to produce them during recall. This allows more time for the memory trace to deteriorate (Ref. c).

(3) The effect of articulatory suppression
When subjects are prevented from rehearsing the items to be remembered, by being required to recite continuously an irrelevant sound such as the word ‘the’, performance declines markedly. Suppression also removes the effect of word length; if the words are not verbally rehearsed, it does not matter how long they take to articulate (Ref. c).

(4) Transfer of information between codes
Because of the efficiency of the phonological store in serial recall, adult subjects typically opt to name and subvocally rehearse visually presented items, thereby transferring the information from a visual to an auditory code. Articulatory suppression prevents this: it removes the effect of phonological similarity for visually presented items, but not for auditory, as these are automatically registered in the phonological store (Ref. d).

(5) Neuropsychological evidence
Patients with a specific deficit in phonological STM behave as if their phonological store is defective. The articulatory rehearsal process is defective in aphasic patients with dyspraxia, because they are unable to set up the speech motor codes necessary for articulation (Ref. e). Dysarthric patients whose speech problems are peripheral, however, show a normal capacity for rehearsal, suggesting that it is the central rehearsal code, rather than its overt operation, that is crucial for rehearsal (Ref. f).

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current WM model has no mechanism that allows this, given that the central executive lacks storage capacity. The data suggest the need for some form of ‘back-up store’[14] that is capable of supporting serial recall, and presumably of integrating phonological, visual and possibly other types of information.

Prose recall

Further problems for the simple phonological loop hypothesis are presented by data on the recall of prose. If asked to recall a sequence of unrelated words, subjects typically begin to make errors once the number of words exceeds five or six. However, if the words comprise a meaningful sentence, then a span of 16 or more is possible[11]. This has of course been known for many years; it presents a good example of what Miller referred to as ‘chunking’[15]. Additional information, typically from long-term memory (LTM), is used to integrate the constituent words into a smaller number of chunks with capacity being set by the number of chunks rather than the number of words. This emphasizes once again the question of how information from different sources is integrated, raising the additional question of where the chunks are stored: are they held in the phonological loop, in LTM, or in some third back-up store?

If they reside within the phonological loop, then a patient whose loop capacity is limited to a single word should show no advantage for sentential sequences. In fact, patient ‘PV’, who has a word span of one word, has a sentence span of five[16]. Note that this is far smaller than the fifteen or so that one would normally expect. Given that her LTM appears to be quite normal, this argues against the idea that chunking is a purely LTM phenomenon. This leaves a back-up store interpretation as the simplest interpretation, although some form of complex interaction between the loop and LTM cannot be ruled out. Such an interpretation would also, however, need to account for data on the recall of longer sequences of prose, where performance is measured in terms of gist rather than by verbatim recall.

The immediate recall of a prose paragraph, typically comprising some 15–20 ‘idea units’, is an important component of many clinical measures of memory. Patients are asked to recall the passage immediately after hearing it, and again after a filled delay of some 20 minutes. Severely amnesic patients are uniformly bad at delayed prose recall. In some cases, however, immediate recall can be virtually normal[17]. Preserved immediate recall appears to demand preserved intelligence and/or the absence of impairment in the functioning of the central executive system[18].

The amount of recalled material far exceeds the capacity of the phonological loop, particularly in view of the fact that the process of recall would be likely to overwrite material already in the phonological store. An account in terms of the visuospatial sketchpad encounters problems, in terms of the limited capacity of the sketchpad, its unsuitability for serial recall, and the lack of any evidence that suggests that only imageable sequences can be recalled. A third possibility might appear to be storage within the central executive. However, this is assumed to be an attentional control system with no intrinsic storage capacity.

Our provisional interpretation of preserved immediate prose recall in densely amnesic patients was in terms of some form of temporary activation of LTM, along lines similar to those suggested by Ericsson and Kintsch[19] who proposed a form of long-term working memory. We agreed with their view that the comprehension of prose passage involves the activation of existing structures within long-term memory, ranging from those at the level of the word or phrase up to conceptual schemas, such as those proposed by Bartlett[20] and subsequently by Schank[21]. It is not clear, however, how simple reactivation of old knowledge is capable of creating new structures, which can themselves be manipulated and reflected upon. I could, for instance, ask you to consider the idea of an ice-hockey-playing elephant, something which you have presumably not encountered too frequently in the past. This would raise the question of how he would hold the stick, and what would be his best position; he could no doubt deliver a formidable body check, but might be even better in goal. In order to solve this team-selection problem, it is necessary to maintain and manipulate the relevant knowledge of elephants and ice hockey. This process could in principle occur in LTM. However, there is no evidence to indicate that patients with normal intelligence combined with grossly impaired LTM have any difficulty in creating the long-term representations necessary for either problem solving or immediate recall, an activity that appears to be limited more by executive processes[18]. Might this process of creating and manipulating mental models also be a useful role for some kind of back-up store?

Although the examples so far have all depended on the recall of prose, similar phenomena have been reported in other domains. For example, Tulving (pers. commun.) reports the claim of a densely amnesic patient to continue to be able to play a good game of bridge. When Tulving tested this, he observed that the patient was not only able to keep track of the contract, but also of which cards had been played; indeed, he and his partner won the rubber. Once again, we appear to have evidence for a temporary store that is capable of holding complex information, manipulating it and utilizing it over a time scale far beyond the assumed capacity of the slave systems of WM.

The problem of rehearsal

One feature of the initial phonological-loop model is its assumption of separable processes of storage and rehearsal, with the latter being broadly equivalent to uttering the material to be recalled subvocally (see Box 2). Strong support for this view came from the effect on serial recall of articulatory suppression and its interactions with the word-length effect (the fact that it is easier to recall a sequence of short words than long words). Alternative accounts of the word-length effect have been presented recently[22], but in my view have difficulty accounting for the interaction of length with articulatory suppression. More problematic for our interpretation of rehearsal in terms of subvocalization are the data suggesting that some kind of rehearsal occurs in children before they have acquired the adult subvocal rehearsal strategy[23]. Even more problematic is the difficulty of giving a good account of rehearsal in the visuospatial sketchpad, and of course, in the suggested back-up store. Hence, while not wishing to abandon the assumption of subvocal rehearsal, the evidence suggests that it may not be typical of other aspects of WM.

Subvocal rehearsal of materials such as a digit sequence offers two probable advantages over rehearsal in other modalities. The first of these concerns the fact that subjects can literally regenerate digits by speaking them, a process that also appears to be possible in a covert form, equivalent to running the speech output programme[24]. Secondly, digits and words involve existing lexical representations, allowing any deterioration in the memory trace to be repaired during the process of rehearsal. Thus, if I am recalling a digit sequence and remember one of the items as *-ive*, then I know the correct item has to be the digit *five*, and not *ive*, *mive* or *thrive*.

In the case of the visuospatial sketchpad, although there has been speculation as to the possible role of eye movements, there is no firm evidence for a specific output process equivalent to vocalization. In contrast to verbal memory studies, the material in most visual memory experiments does not comprise familiar shapes or objects, as these tend to be nameable, which would allow subjects to recode the material verbally so as to take advantage of the capacity of the phonological loop for storing serial order.

It therefore seems more plausible to assume some form of general rehearsal, which perhaps involves the sequential attention to the component of the material to be recalled. In the case of an abstract pattern, this might involve chunking into a number of subcomponents. In the case of a prose passage, it presumably involves attending to the structure that has been built in order to represent the passage as part of the process of comprehension[19]. Hence, although additional assumptions will need to be made about the process of rehearsal operating within the proposed back-up store, similar assumptions are already necessitated by the question of rehearsal in the sketchpad.

Consciousness and the binding problem

Although the question of conscious awareness was not tackled directly, the WM model was implicitly assumed to play a role in consciousness. For example, the visuospatial sketchpad was assumed to be involved in the storage and manipulation of visual images, and the phonological loop to play an equivalent role in auditory–verbal imagery[25]. Baddeley and Andrade[26] recently attempted to explore this assumption in a series of experiments in which subjects were required to maintain auditory or visual images and rate their vividness, while at the same time performing tasks selected to disrupt selectively either the visuospatial or phonological slave systems. Our results indicated that the relevant systems were indeed involved in conscious awareness, but suggested in addition a substantial role for LTM and for the central executive. These results reinforced the view that aspects of conscious awareness can be studied empirically, with highly coherent results. In doing so, they supported the WM framework as a useful empirical tool, whilst at the same time exposing its limitations. The model had no means of storing the complex images other than the two slave systems, which clearly play a role in the maintenance of verbally cued images, but one that is not nearly as important as the contribution of LTM. Once again, this suggests the existence of a store that is capable of drawing information both from the slave systems and from LTM, and holding it in some integrated form.

Such a process was indeed implicit in an earlier attempt to give an account of conscious awareness in terms of the WM model. Baddeley[27] suggested that WM might play an important role in solving the binding problem – the question of how information from a range of separate independent sensory channels is bound together to allow the world to be perceived as comprising a coherent array of objects. Such a process requires the integration of information regarding the perceived location, colour, movement, smell and tactile features of objects. It was suggested that the central executive played a crucial role in such integration, although neglecting the fact that the executive contained no short-term multimodal store capable of holding such complex representations.

To summarize, although the visual and verbal slave systems of the WM model do offer a plausible account of a wide range of data, evidence from patients with short-term memory deficits, from the resistance in serial recall to articulatory suppression, and from the recall of prose, all suggest the need to assume a further back-up store. Evidence for the integrated storage of information from different modalities and systems comes from the small but significant impact of visual similarity on verbal recall, and from the very substantial impact of meaning on the immediate recall of sentences and prose passages. There is a clear need, therefore, to assume a process or mechanism for synergistically combining information from various subsystems into a form of temporary representation. Such a representation also offers a possible solution to the binding problem and the role of consciousness. The term 'episodic buffer' is proposed for this suggested fourth component of the working memory model.

The episodic buffer

The episodic buffer is assumed to be a limited-capacity temporary storage system that is capable of integrating information from a variety of sources. It is assumed to be controlled by the central executive, which is capable of retrieving information from the store in the form of conscious awareness, of reflecting on that information and, where necessary, manipulating and modifying it. The buffer is episodic in the sense that it holds episodes whereby information is integrated across space and potentially extended across time. In this respect, it resembles Tulving's concept of episodic memory[28]. It differs, however, in that it is assumed to be a temporary store that can be preserved in densely amnesic patients with grossly impaired episodic LTM. It is, though, assumed to play an important role in feeding information into and retrieving information from episodic LTM. The model of WM incorporating the episodic buffer is illustrated in Fig. 1.

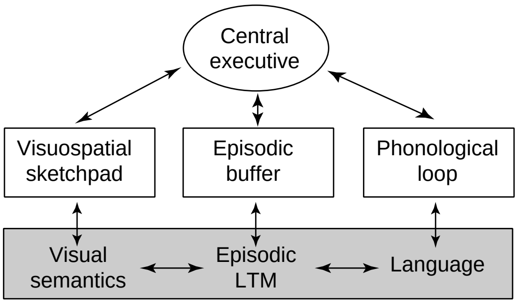

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Fig. 1. The current version of the multi-component working memory model. The episodic buffer is assumed to be capable of storing information in a multi-dimensional code. It thus provides a temporary interface between the slave systems (the phonological loop and the visuospatial sketchpad) and LTM. It is assumed to be controlled by the central executive, which is responsible for binding information from a number of sources into coherent episodes. Such episodes are assumed to be retrievable consciously. The buffer serves as a modelling space that is separate from LTM, but which forms an important stage in long-term episodic learning. Shaded areas represent 'crystallized' cognitive systems capable of accumulating long-term knowledge, and unshaded areas represent 'fluid' capacities (such as attention and temporary storage), themselves unchanged by learning.

The component proposed is a buffer in that it serves as an interface between a range of systems, each involving a different set of codes. It is assumed to achieve this by using a common multi-dimensional code. The buffer is assumed to be limited in capacity because of the computational demand of providing simultaneous access to the necessarily wide range of different codes[29].

The episodic buffer can be accessed by the central executive through the medium of conscious awareness. The executive can, furthermore, influence the content of the store by attending to a given source of information, whether perceptual, from other components of working memory, or from LTM. As such, the buffer provides not only a mechanism for modelling the environment, but also for creating new cognitive representations, which in turn might facilitate problem solving.

How is the buffer implemented biologically?

Of the various speculations as to the biological mechanism of binding, I would regard the process of synchronous firing as providing one promising hypothesis[30]. I would not expect the buffer to have a single unitary anatomical location; given its putative importance, some redundancy would be biologically useful in making the system more robust. However, frontal areas are very likely to be important for both the central executive and the episodic buffer, as evidenced by behavioural data on the operation of executive processes in general[31], together with fMRI studies implicating areas within the right frontal lobes in the capacity to combine two separate tasks. A recent fMRI study by Prabhakaran *et al.*[32] compared the retention of verbal and spatial information held in an integrated or unintegrated form. The results showed greater right frontal activation for integrated information, with unintegrated retention showing more posterior activation of areas previously implicated in verbal and spatial WM. Prabhakaran *et al.* conclude that 'The present fMRI results provide evidence for another buffer, namely, one that allows for temporary retention of integrated information' (Ref. 32, p. 89).

So what's new?

The proposal of the episodic buffer clearly does represent a change within the working memory framework, whether conceived as a new component, or as a fractionation of the older version of the central executive. By emphasizing the importance of coordination, and confronting the need to relate WM and LTM, it suggests a closer link between our earlier multi-component approach and other models that have emphasized the more complex executive aspects of WM. The revised framework differs from many current models of WM in its continued emphasis on a multi-component nature, and in its rejection of the suggestion that working memory simply represents the activated portions of LTM (Ref. 33). It also rejects the related view that the slave systems merely represent activations within the processes of visual and verbal perception and production[34,35]. Although WM is intimately linked both to LTM and to perceptual and motor function, it is regarded as a separable system involving its own dedicated storage processes.

Some outstanding issues

What problems are raised by the proposed new component of WM? I would suggest, first of all, that there is an immediate need to investigate its boundaries. Why not assign all memory to the episodic buffer, for example? I suggest that the existing evidence for the fractionation of WM, including that from neuropsychology and neuroradiology, indicates that this would be a thoroughly retrograde step[6]. It is less clear, however, whether one can draw a clear line between the two slave systems of WM and the episodic buffer. Fortunately, tools already exist for answering this kind of question, making use of neuropsychological cases with specific phonological or visuospatial memory deficits, and by using dual-task interference procedures. Such procedures are, of course, rarely process-pure, typically having at least some central executive component. However, by using the same secondary tasks to study both visuospatial and phonological memory, it is possible to tease apart the specific contribution from each slave system from the contribution of the executive component[26].

Separation of the episodic buffer from episodic LTM presents another problem. It seems likely that the study of selected neuropsychological patients will prove most productive, contrasting cases with executive deficit but preserved LTM with pure amnesic patients. Here and elsewhere, it seems likely that neuroradiological imaging could provide an additional valuable tool in association with the study of single case studies, and experimental conditions in which the LTM and WM component can be differentially controlled.

The episodic buffer emphasizes the integration of information, in contrast to earlier approaches to WM, which have focused on separating the various components. We need now to know much more about the role of executive processes in chunking. In connection with this, we need to be able to separate the relatively automatic binding of properties that occur in the processes of normal perception from the more active and attentionally demanding integrative processes that are assumed to play such an important role in the episodic buffer[29]. As Prabhakaran *et al.* have shown[32], neuroradiological measures have considerable potential for investigating the processes underlying this capacity, and the study of patients with executive deficits following frontal lobe damage also offers a promising line of investigation[31].

The suggestion that the episodic buffer forms the crucial interface between memory and conscious awareness places it at the centre of the highly active line of research into the role of phenomenological factors in memory and cognition. Tulving[28], for example, defines his concept of episodic memory explicitly in terms of its associated phenomenological experience of remembering. Although not all theorists would wish to place phenomenological experience so centrally, there is increasing evidence to suggest that conscious monitoring of the evidence supporting an apparent memory plays a crucial role in separating accurate recall from false memory, confabulation and delusion[36]. If the episodic buffer does indeed provide the storage, and the central execu-tive the underlying processing for episodic memory, then unravelling their complexities is likely to provide a fruitful and potentially tractable activity for many years to come.

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Forward modeling allows feedback control for fast reaching movements

Michel Desmurget and Scott Grafton

Delays in sensorimotor loops have led to the proposal that reaching movements are primarily under pre-programmed control and that sensory feedback loops exert an influence only at the very end of a trajectory. The present review challenges this view. Although behavioral data suggest that a motor plan is assembled prior to the onset of movement, more recent studies have indicated that this initial plan does not unfold unaltered, but is updated continuously by internal feedback loops. These loops rely on a forward model that integrates the sensory inflow and motor outflow to evaluate the consequence of the motor commands sent to a limb, such as the arm. In such a model, the probable position and velocity of an effector can be estimated with negligible delays and even predicted in advance, thus making feedback strategies possible for fast reaching movements. The parietal lobe and cerebellum appear to play a crucial role in this process. The ability of the motor system to estimate the future state of the limb might be an evolutionary substrate for mental operations that require an estimate of sequelae in the immediate future.

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Since the early contribution of Woodworth[1], the degree to which visually-directed movements are planned in advance or controlled online during their actual execution has been an issue of considerable debate[2–6]. After almost a century of controversy, the relative importance of three different models, namely the feedforward, feedback and hybrid, continues to be argued. Feedforward models propose that a motor command is defined in advance of the onset of

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