WORKING MEMORY: LOOKING BACK AND LOOKING FORWARD

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The concept of working memory proposes that a dedicated system maintains and stores information in the short term, and that this system underlies human thought processes. Current views of working memory involve a central executive and two storage systems: the phonological loop and the visuospatial sketchpad. Although this basic model was first proposed 30 years ago, it has continued to develop and to stimulate research and debate. The model and the most recent results are reviewed in this article.

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The theoretical concept of working memory assumes that a limited capacity system, which temporarily maintains and stores information, supports human thought processes by providing an interface between perception, long-term memory and action[1–3]. There are many approaches to the study of working memory, using a range of empirical and theoretical techniques. However, most theories agree on the need for a system of limited attentional capacity, supplemented by more peripherally-based storage systems[4]. The account that follows emphasizes this fractionation, stressing the importance of executive control, but concentrating initially on the more tractable peripheral storage systems. Within experimental cognitive psychology there are several different but complementary approaches to working memory: some emphasize the role of attentional control in memory[5], whereas others attempt to explain working memory data in terms of models that were originally developed for long-term memory (LTM)[6,7]. An example of this approach is provided by Nairne[8], whose account seems to criticize the multi-component model of working memory. However, most of Nairne's criticisms apply only if one attempts to explain all the phenomena of working memory in terms of the phonological loop — one component of a complex system. As this review shows, the phonological loop has received more attention than other components, but this reflects its relative tractability, compared with the visuospatial and executive subsystems. A third, influential approach relies on correlational techniques that capitalize on individual differences across the various components of working memory (BOX 1). Rather than attempting to give an account of each of these approaches, I describe a single multi-component model of working memory. In general, deviations from the other models represent difference of emphasis and scope, rather than direct conflict. Points of clear disagreement will, however, be identified and discussed.

The term 'working memory' seems to have been invented by Miller, Galanter and Pribram[9], and was adopted by Baddeley and Hitch[10] to emphasize the differences between their three-component model and earlier unitary models of short-term memory (STM). These differences include its multi-component character, its emphasis on combined processing and storage, and the stress on its functional importance as a system that facilitates a range of cognitive activities, such as reasoning, learning and comprehension. This approach resulted in the development of a set of experimental tasks that could be used to analyse different activities and subject populations[1]. Because the available empirical evidence provided few constraints, the model was initially loosely specified: for example, it had no mechanism for storing serial order. However, it was simple and robust, and had the potential to develop and become much richer and more clearly specified. The Baddeley and Hitch model continues to flourish, and will be used as a basis for this review. The article will, however, extend beyond

Box 1 | Individual differences in working memory

In 1980, Daneman and Carpenter[164] developed a task in which subjects were required to combine storage and processing, first reading a series of unrelated sentences, and then recalling the final word of each. Working memory span was defined as the maximum number of sentences for which this task could be performed perfectly. They found a high correlation between working memory span and reading comprehension, a result that has been replicated many times[165]. Similar results occur when sentence processing is replaced by other tasks, such as arithmetic calculation[166] or colour–word association[167]. Prediction is not limited to comprehension but extends from spelling[168] to acquisition of logic[169], and from note taking[170] to following directions[171], with correlations typically being in the region of 0.5. Kyllonen and Christal[172] compared a cluster of working memory span measures with more conventional measures of intelligence based on reasoning. They found a high correlation, with the main difference being a slightly higher reliance of working memory span on processing speed, and of reasoning on previous knowledge.

Although much of the work in this area has simply assessed the correlation between working memory span and performance on cognitive tasks, there is a growing interest in understanding the underlying processes that contribute to the relatively complex working memory span task. Studies using factor analysis and latent variable analysis have supported the broad concept of separate phonological[173] and visuospatial storage systems[174], together with a main executive system. Attention is now focusing on the processes that underlie executive control[173,175,176].

Theories of intelligence have typically been developed as statistical models of data from large batteries of tests. These methods have been used to address controversies such as whether intelligence is best regarded as a single general capacity (*G*), as proposed by Spearman[177], or as a range of separate capacities, as proposed by Thurstone[178]. A meta-analysis by Carroll[179] of more than 400 studies has identified three components, one resembling Spearman's *G*, one visuospatial and one verbal-arithmetic. The analogy with the three-component working memory model is clear. Although extremely successful practically, the psychometric study of intelligence seems, in recent years, to have generated more political controversy than theoretical progress[180,181]. Applying the sophisticated statistical methods that have been developed within psychometrics to the experimentally and neuropsychologically grounded multi-component working memory model might be a fruitful way forward.

the range of the model to speculations as to the probable future development of a more general theory of working memory.

The multi-component model of working memory

In 1949, Hebb[11] proposed a distinction between STM, which is based on temporary electrical activation, and LTM, which is based on neuronal growth. A decade later, support for this distinction came from studies showing that small amounts of information were rapidly forgotten unless actively rehearsed[12,13]. A counter attack[14] argued that results such as these could be explained in terms of a unitary LTM system, but in the mid-1960s many studies argued for a separation between LTM and STM[15]. By the late 1960s, many new models had emerged around the concept of STM. The most influential model[16] proposed that information from the environment flows through a series of temporary sensory registers into a limited capacity short-term store (STS), which feeds information into and out of LTM. This system was also assumed to act as a working memory, supporting complex cognitive activities, although this aspect was not further explored.

This model encountered problems both in terms of its assumptions regarding learning[17], and from data concerned with the impact of neuropsychological damage to the STS. If the STS served as a unitary working memory, then patients with STS impairment should show little capacity for long-term learning or for everyday cognitive activities. Such patients were identified[18], but had few cognitive problems beyond grossly impaired STM[19].

Baddeley and Hitch[10] used secondary tasks to deplete the availability of STM in subjects performing tasks, such as reasoning or learning, that were assumed to rely on working memory. They found clear but far from catastrophic impairment, and proposed a three-component model of working memory in place of the unitary system. The three components (FIG. 1) comprised a control system of limited attentional capacity, termed the central executive, which is assisted by two subsidiary storage systems: the phonological loop, which is based on sound and language, and the visuospatial sketchpad.

In this review, I focus on each of these components in turn, emphasizing in particular those aspects that have developed or changed in recent years.

The phonological loop

Structure of the loop. The model of the phonological loop comprises a phonological store, which can hold memory traces for a few seconds before they fade, and an articulatory rehearsal process that is analogous to subvocal speech (FIG. 2). Memory traces can be refreshed by being retrieved and re-articulated. Immediate memory has a limited span because articulation takes place in real time — as the number of items rehearsed increases, it reaches a point at which the first item will have faded before it can be rehearsed. Much of the work in this area has used immediate serial recall, typically using a small set of digits, letters or unrelated words, with the characteristics of the material remembered being used to give an indication of the nature of the code on which the recall is based. For unrelated letters, the code is acoustic or phonological; sequences of similar sounding letters such as V, B, G, T, P, C are recalled less well than a dissimilar set, such as W, X, K, R, Y, Q[20,21]. Similarity of sound is also crucial for unrelated words, whereas meaning is relatively unimportant[22]. When the model is switched from STM to LTM using several presentations of longer lists, sound becomes irrelevant and meaning crucial[23].

Evidence for the role of articulation comes from the word-length effect: immediate memory span declines as word length increases from one to five syllables[24]. The suggestion that this reflects the slower rehearsal of

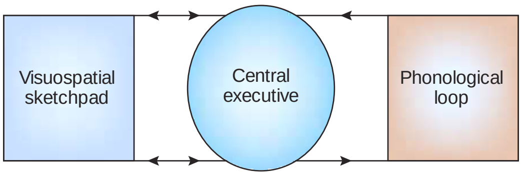

Figure 1 | **The three-component model of working memory.** This model, proposed by Baddeley and Hitch[10], comprises a control system, the central executive, and two storage systems, the visuospatial sketchpad and the phonological loop.

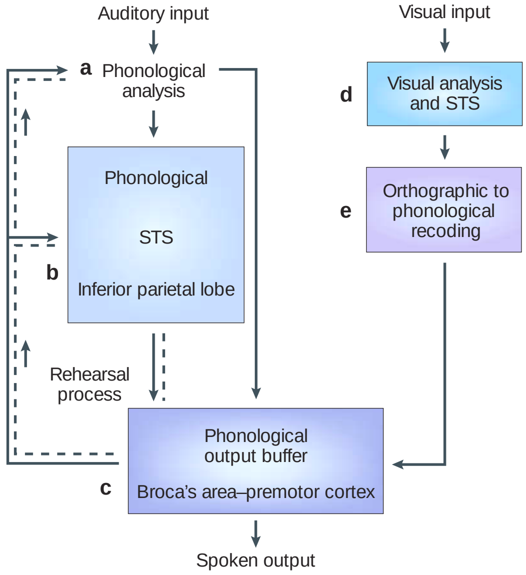

Figure 2 | **A functional model of the phonological loop.** **a** | Phonological analysis. **b** | Short-term storage (STS). **c** | The programming of speech output. **d** | Visual encoding. **e** | Grapheme-to-phoneme conversion. Auditory information gains direct access to a phonological store, after which it passes to an output buffer for recall or recycling through rehearsal. Visual material can be recoded verbally and then gain access to the phonological store through rehearsal. Modified, with permission, from REF. 19 © (2002) John Wiley & Sons Ltd.

longer words is supported by the abolition of the word-length effect when subvocal rehearsal is prevented by requiring subjects to repeat an irrelevant sound[24,25].

The two-component model of the loop is also supported by neuropsychological evidence (see REF. 19 for a recent review). Patients with phonological STM deficits in the absence of more general language impairment typically have lesions in the left temporoparietal area (BRODMANN AREA (BA) 40). When words are presented visually, these patients show neither a phonological similarity effect nor a word-length effect, a pattern of behaviour that is consistent with their avoiding the use of the defective phonological store, despite having a normal capacity to articulate[26]. Subvocal rehearsal does not seem to depend on the capacity for peripheral control of articulation, as it can be preserved in ANARTHRIC patients who have lost the capacity for overt articulation[27]. On the other hand, DYSPRAXIC patients who have lost the capacity to set up internal speech–motor programmes do show the predicted reduction in memory span[28].

Although the two-component model of the loop gave a good account of a range of evidence, it was a limited model that left three crucial questions unanswered. How is serial order maintained? How does the loop interact with LTM? And what is the biological function of the phonological loop?

The problem of serial order

Explanations of how serial order is remembered, learned and retrieved fall into two broad categories: chaining models and contextual models[29,30]. Chaining interpretations assume that each item forms a cue or stimulus for the following item, with the result that once the initial item is activated, the sequence runs off relatively automatically[31,32]. Such models have difficulty in dealing with sequences in which the same item recurs (7, 1, 9, 3, 1, 5, 8), which leads to a slight impairment in performance[33]. More problematic for chaining models is the pattern of data that is observed when phonologically similar and dissimilar items are interleaved (C, X, P, W, D, Y). According to chaining models, similarity should cause confusion among similar stimuli, leading to the cueing of the wrong responses. Errors should therefore follow similar letters and involve the dissimilar items. In fact, performance on dissimilar items is unaffected by the interleaving of similar items, which continue to show a higher error rate[30,34].

A range of computationally explicit models of verbal STM have been proposed[6,7,31], with several based on the phonological loop concept[35–38]. Burgess and Hitch[36] assume that order is carried by associating successive items with an ongoing contextual cue, the exact nature of which is unspecified. The phonological similarity effect occurs because the items that are specified by each cue are encoded phonologically, with similar items having fewer distinguishing cues. The similarity effect is assumed to occur at retrieval rather than at the cueing stage.

The Page and Norris model[38] assumes that recall of order is based on positional associations between the first and subsequent items. The associations become progressively weaker as more items are added, providing a simple explanation for limited memory span. Retrieval involves competitive queueing: the strongest association is retrieved first and the associated item is emitted and then inhibited, allowing the next strongest to be retrieved and so on to the end of the list, or to the point at which the associations become too weak and the process breaks down. A related model that also uses serial position as its context is Henson's start–end model[37], in which both the first and last items act as cues.

All of the contextual models give good accounts of the distribution of intrusion errors, whereby the most common error is for two items to transpose (present 1, 2, 3, 4, 5, 6; recall 1, 2, 3, 5, 4, 6). Henson's model, however, gives a better account of what he calls protrusions, a tendency for an omitted item to be replaced by an item in the same serial position within the previous list (present 1, 2, 3, 4, 5, recall 1, 2, 3, 4, 5; then present 6, 7, 8, 9, 0, recall 6, 7, 3, 9, 0). It seems possible, however, that this reflects a separate, more long-term component, as discussed later.

Despite differences in the nature of the contextual cues, computationally explicit models are possible, and they typically separate the mechanism for storing order from the mechanism by which the items are registered. Bearing this in mind, we should return to the basic phenomena that prompted the model.

The phonological similarity effect. The phonological similarity effect is highly robust[39], and is often used as a marker of the phonological loop. It tends to disappear

BRODMANN AREAS
(BA). Korbinian Brodmann (1868–1918) was an anatomist who divided the cerebral cortex into numbered subdivisions on the basis of cell arrangements, types and staining properties (for example, the dorsolateral prefrontal cortex contains subdivisions, including BA 46, BA 9 and others). Modern derivatives of his maps are commonly used as the reference system for discussion of brain-imaging findings.

ANARTHRIC
Unable to speak because of defective articulation.

DYSPRAXIC
Having an impairment of the ability to perform certain voluntary movements, often including speech.

when error rates increase beyond around 50%, indicating that subjects are abandoning the loop and opting for alternative strategies such as sematic or visual coding [40,41]. Given the importance of strategy, there have been surprisingly few attempts to control it by instruction, with the notable exception of Hanley and Bakopoulou[42]; we are likely to see more such studies, preferably backed up by neuroimaging measures.

The word-length effect. Although almost as robust as the phonological similarity effect[39], the word-length effect is open to a wider range of interpretations[43]. One approach has been to reject time-based decay, arguing that long words are more difficult to recall because they contain more components and are therefore more fragile[44,45]. When long and short words are mixed, however, long words are no more difficult to remember than their shorter neighbours, with recall depending on overall list duration, as predicted by the loop hypothesis[46]. Finally, the abolition of the word-length effect for either auditory or visual presentation, when rehearsal is suppressed[24,47], fits more naturally into the phonological loop model than into its competitors.

Less radical modifications of the model have also been proposed. It has been suggested that the word-length effect stems largely[43,46], or even entirely[48], from delay during output, rather than from rehearsal. Recent experiments controlling output time, however, implicate both, as the loop model would predict[47].

The assumption that forgetting in the phonological store reflects trace decay has also been challenged. Evidence for time-based decay came initially from a study comparing recall of disyllabic words that were spoken quickly (bishop, tipple) or slowly (harpoon, Friday)[24]. As predicted, longer duration words were less well recalled. However, there were failures to replicate this using other sets of simuli[28,49]. It is possible that, in these studies, spoken duration was not adequately measured, and the two sets were not equated for phonological similarity[50] (but see REF. 51), but other studies using different sets of study words further questioned the importance of duration relative to other factors such as linguistic complexity[52]. However, the most methodologically rigorous study so far, which considered the whole range of materials that have been used previously, concluded that when duration and similarity are measured carefully, all sets of material give results that can be accounted for in terms of spoken duration and phonological similarity[53]. It seems, therefore, that the simple trace decay assumption, though controversial, is still adequate, obviating the need for more complex interference models.

Irrelevant sound effects. Immediate recall is impaired by the concurrent or subsequent presentation of irrelevant spoken material[7,54–57]. This was initially interpreted in terms of mnemonic masking within STM[57,58]. However, irrelevant speech had no greater effect on phonologically similar items than on dissimilar items[59], and performance was unaffected by phonological similarity between the material to be remembered and the spoken items to be ignored[60–62]. This prompted alternative interpretations of the effect[7,41,55,63]. Jones and colleagues[55,63] have found that the effect is not limited to speech or music, but can also be produced by variable tones. The crucial requirement seems to be a fluctuation in the state of the irrelevant stimulus stream. They suggest that this sets up a competing representation that disrupts the storage of serial order.

The proposal of separate item and order mechanisms in the phonological loop allows a range of explanations of the irrelevant sound effect[40]. A detailed account within the primacy model of the phonological loop is given by Page and Norris[64], but this remains an area of lively controversy[41,65]. Indeed, Jones and colleagues deny the need to assume separate visual and verbal storage systems[65], although the evidence they cite has not proved readily replicable, and their model fails to give a good account of data from neuropsychological and neuroimaging studies[40].

Function of the phonological loop. We have proposed that the phonological loop evolved to facilitate the acquisition of language[66]. Evidence for this view came initially from the failure of a patient with a pure phonological loop deficit to acquire the vocabulary of a new language, despite otherwise normal verbal LTM[66]. It was supported by the demonstration that factors that disrupt the phonological loop — such as articulatory suppression, phonological similarity and word length — also disrupt the acquisition of foreign vocabulary, but not of learning to associate pairs of unrelated native language words; such learning is typically based on semantic coding[67,68]. Phonological loop capacity is a good predictor of the ability of children[69] and adults[70] to learn a second language.

Acquisition of native vocabulary in children is well predicted by non-word repetition, the capacity to hear and repeat back an unfamiliar pseudo-word, which is assumed to depend on the phonological loop[71,72]. Children with a specific language disability, coupled with normal non-verbal intelligence, also perform badly on non-word repetition, but have no obvious hearing or articulatory problems[73]. This and further evidence led to our proposal that the phonological loop evolved to facilitate language acquisition[66].

Most studies of verbal STM rely on the retention of sequences of items such as digits and letters that are already familiar. If we are correct, however, this system has evolved to master new words, comprising unfamiliar sequences of phonemes. Studies within the field are therefore beginning to focus strongly on the sublexical level of analysis, and on the more detailed structure of the phonological loop system[74,75]. There are two main questions: how temporary storage can enhance the learning of new words, and conversely, how language influences STM.

Immediate recall of non-words is better when they are similar in phonotactic structure to the native language of the person remembering[76]. This indicates that long-term implicit knowledge can be used to aid immediate recall. However, performance on phonotactically unfamiliar items was much better at predicting subsequent vocabulary acquisition than performance on phonotactically familiar items. It is possible that both types of material depend on the phonological store, which is responsible for long-term learning, but that the articulatory output process can also benefit from previous language habits. Support for this view came from a study in which immediate memory for words and non-words was measured using either recall or recognition. Sequences of words show a clear advantage over non-words for spoken recall, but there is virtually no difference for serial-order recognition[74,77]. This indicates that language habits influence performance through the articulatory output component of the phonological loop, whereas the storage component is comparatively language independent. This could be advantageous for a system that has evolved to acquire new words, without being excessively influenced by existing knowledge. So, the phonological loop should facilitate language acquisition in two ways: the store should provide relatively unconstrained temporary representation for new phoneme sequences, and the articulatory system should facilitate learning through rehearsal, provided that the new sounds can be represented using existing output processes. This faciliation is likely to occur immediately for phonotactically regular sequences, but might require further exposure when the sequences are irregular and unfamiliar.

The simple phonological loop model has proved to be robust and productive. Future developments seem likely to link it more directly to theories of language perception and production.

The visuospatial sketchpad

Like its verbal equivalent, visual working memory is limited in capacity, typically to about three or four objects. This results in the phenomenon of change blindness, whereby objects in scenes can change colour, move or disappear without people noticing[78,79]. The visual world typically persists over time, and itself provides a continuing memory record, making detailed visual retention largely redundant[80]. Objects comprise features such as colour, location and shape, with features within a given dimension competing for storage capacity, whereas features from different dimensions do not[81,82]. Wheeler and Triesman[83] propose a model whereby feature values are stored in parallel dimension-specific registers or caches, with competition within but not between such registers. Retention of objects is dependent on the binding together of constituent features, a process that demands attention.

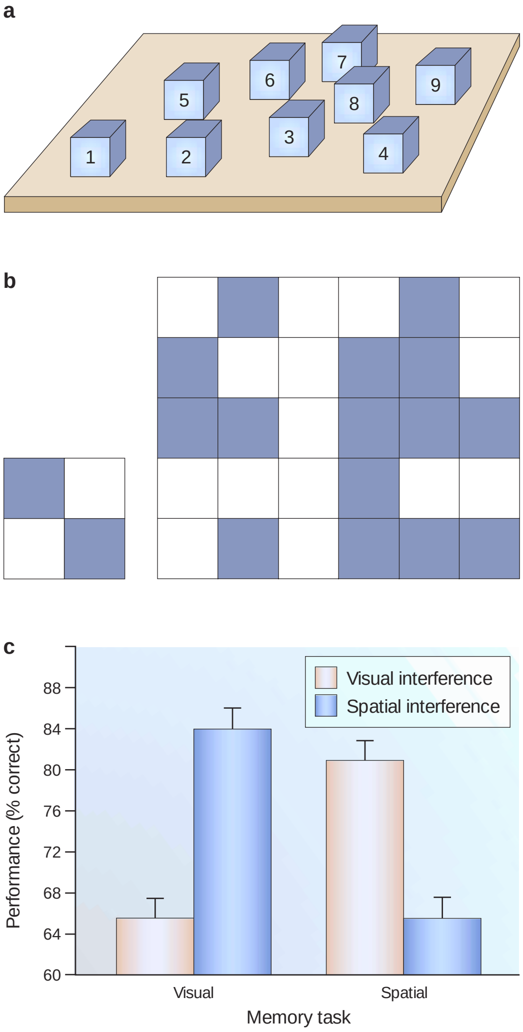

Figure 3 | **Visual and spatial short-term memory tasks.** **a** | Spatial short-term memory is measured using the Corsi block tapping test. The tester taps a sequence of blocks, which the subject attempts to imitate. Sequence length increases until performance breaks down. Testing is facilitated by the numbers on the tester's side of the blocks. Digit span is typically about two more than Corsi span. **b** | Spatial span involves presenting the subject with a series of matrices in which half the cells are filled. The pattern is removed and the subject is required to mark the filled cells on a response sheet. The size of the matrices is steadily increased until performance breaks down. **c** | Effects of interference from visual or spatial stimuli on Corsi and pattern span. Corsi span is disrupted by spatial activity and pattern span by visual activity. Panels **b** and **c** modified, with permission, from REF. 85 © (1999) Elsevier Science.

The visual–spatial distinction. Neuropsychological studies have indicated the need to distinguish between visual and spatial memory. The Corsi block task measures spatial span. It comprises an array of nine blocks; the experimenter initially taps two of them, and the subject attempts to imitate the sequence, with sequence length increasing until performance breaks down[84] (FIG. 3a). The visual, non-spatial counterpart of this task is pattern span, in which the subject is shown matrices of cells of which a random 50% are filled (FIG. 3b). The matrix is then removed, and the subject attempts to recall which cells were filled. Testing begins with a 2 × 2 matrix, with the matrix size increasing until performance breaks down. Della Sala *et al.*[85] have shown a double dissociation between visual and spatial span. For normal subjects, the Corsi task is disrupted more by spatial than visual interference, whereas the reverse is true for pattern span (FIG. 3c). Neuropsychological cases have also been identified, showing either disruption of visual but not spatial STM, or the opposite pattern[86].

Although the most common distinction is between visual and spatial coding, Smith *et al.*[87] prefer a distinction between the spatial and object codes, linking the two to the separate visual processing paths that are proposed for the encoding of 'what' and 'where' information[88]. This idea is supported by neuroimaging studies, which broadly fit the predicted pattern, although other interpretations are possible[86]. Another characterization is in terms of a dynamic (spatial) and static (pattern) distinction[89]. To complicate matters further, a kinaesthetic or motor dimension of coding has also been proposed[90]. This is an area that is likely to benefit from careful studies that aim to separate out these potential contributions to visuospatial STM, preferably accompanied by careful and systematic neuroimaging.

Visual imagery. We can, of course, set up visuospatial representations from verbal instructions, such as when attempting to describe a familiar room or reading a visually descriptive passage from a novel. A number of techniques have been developed to investigate visuospatial imagery. One is illustrated in FIG. 4. The subject's task is to remember and repeat back a sequence of sentences while viewing a matrix in which one cell is denoted the starting square. Under one condition, the sentences can be recoded as a path through the matrix, whereas in the second the crucial adjectives are non-spatial and rely on rote verbal memory. Typically subjects can remember eight spatial sentences, but only six non-spatial ones[91]. The requirement to perform a concurrent tracking task, such as steering a car, disrupts the spatial code, but not the verbal condition. Although this task is predominantly spatial in character, other imagery mnemonics seem to depend much more on visual or pattern memory. Subjects who are required to learn to associate pairs of items (elephant/umbrella) can enhance performance by imagining the two interacting, so that when they are given the word elephant, the umbrella springs to mind. This kind of imagery can be disrupted by simultaneously presenting pictures of objects, patches of colour[91] or even flickering patterns of visual noise[92].

a

Spatial material	**Nonsense material**
In the starting square put a 1.	In the starting square put a 1.
In the next square to the *right* put a 2.	In the next square to the *quick* put a 2.
In the next square *up* put a 3.	In the next square to the *good* put a 3.
In the next square to the *right* put a 4.	In the next square to the *quick* put a 4.
In the next square *down* put a 5.	In the next square to the *bad* put a 5.
In the next square *down* put a 6.	In the next square to the *bad* put a 6.
In the next square to the *left* put a 7.	In the next square to the *slow* put a 7.
In the next square *down* put an 8.	In the next square to the *bad* put an 8.

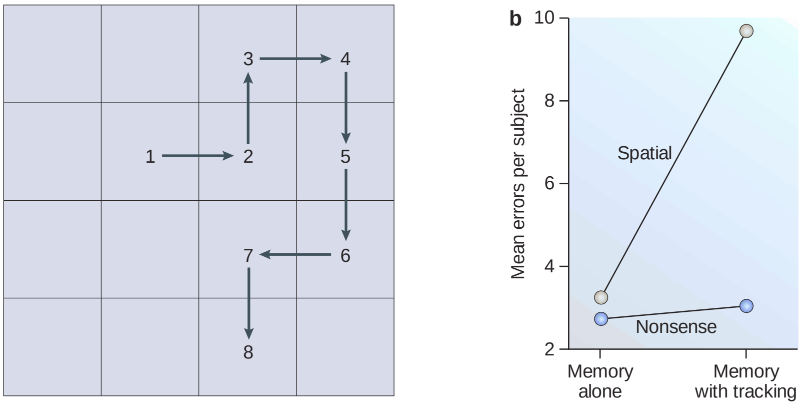

Figure 4 | **The task devised by L. H. Brooks to study the role of visual imagery in verbal recall.** (see REF. 182). **a** | Subjects attempt to recall the sequence of sentences, typically succeeding on around eight sentences when spatially codable material is used, and six with non-spatial material. **b** | Requiring the subject to perform the two memory tasks at the same time as they are tracking a moving light stimulus disrupts the use of visuospatial imagery, but has no effect on remembering the sequence of verbally coded sentences.

Function of the visuospatial sketchpad. The capacity to hold and manipulate visuospatial representations provides a measure of non-verbal intelligence that predicts success in fields such as architecture and engineering[93,94]. There are many examples of the importance of visual or spatial imagery in scientific discovery, including Einstein's development of his general theory of relativity[95]. Attempts to study the design phase of engineering architecture have also identified the role of visuospatial imagery and mental synthesis[93,94]. In recent years, attempts to study the process of mental synthesis experimentally have increased. A typical study might involve presenting the subject with an array of verbally described shapes, for example, the capital letters J and D, and asking the subject to combine them into an object, with size being flexible. A suitable answer might be an umbrella[96,97]. The memory load can be increased by adding further shapes, and by requiring the subject to remember and manipulate them mentally as opposed to allowing the shapes to be drawn[98,99]. A number of studies have applied the working memory framework to such tasks, and have found that subjects will use coding in the phonological loop to store items while manipulating them visuospatially[100], although this might have the disadvantage of losing visuospatial information in the process[101]. By analogy with the role of the phonological loop in language acquisition, it seems plausible to assume that the sketchpad might have a role in acquiring semantic knowledge about the appearance of objects and how to use them, and for understanding complex systems such as machinery, as well as for spatial orientation and geographical knowledge. So far, there seems to have been little work on this potentially important topic.

Fractionation. Logie[102] has proposed a fractionation of the sketchpad that is analogous to that of the loop. He distinguishes between a visual storage component, the visual cache, and a more dynamic retrieval and rehearsal process which he terms the inner scribe. He argues that the sketchpad is not a perceptually-based store, but occurs after visual information has been processed in LTM. Support for this view comes from two types of patient, both showing visuospatial neglect after right hemisphere damage[86]. One type of patient cannot report the contents of their visual left hemifield, but

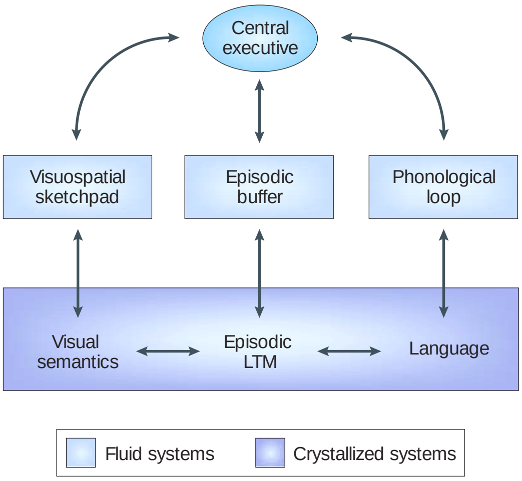

Figure 5 | **The multi-component working memory revision.** The dark purple areas represent long-term or crystallized knowledge. The episodic buffer provides an interface between the sub-systems of working memory and long-term memory (LTM)[125].

show no such occlusion when describing a familiar view from memory, while other patients show the opposite: normal visual attention coupled with neglect of the left hemifield when describing a scene from memory, presumably reflecting impaired scanning of a post-perceptual memory store.

In conclusion, visuospatial working memory is an active but poorly integrated area of research. It would benefit greatly from more interaction among research communities at both a methodological and theoretical level, and from linkage with the extensive literature on visual attention, including work using single-unit recording in non-human primates[103,104].

The central executive

The central executive is the most important but least understood component of working memory. In the original model, it was simply treated as a pool of general processing capacity, to which all the complex issues that did not seem to be directly or specifically related to the two sub-systems were assigned. The first attempt to advance the concept came with the proposal[105] to adopt the Norman and Shallice[106] model of attentional control. This divided control between two processes. The first relied on the control of behaviour by habit patterns or schemas, implicitly guided by cues provided by the environment. The second comprised an attentionally limited controller, the supervisory activating system (SAS), that could intervene when routine control was insufficient. Evidence for control by schema came from slips of action in which a familiar action pattern, such as driving to the office, might take over from a less routine intention, such as driving on a Saturday morning to the supermarket, resulting in taking the wrong route. Evidence for the SAS came principally from the study of patients with frontal lobe damage, which was assumed to result in impaired SAS function and which led to inappropriate perseveration on some occasions, and excessive distractability on others[107–109].

The distinction between automatic, habitual control and attentional, supervisory control is an important one, which can also be linked to extensive evidence from social psychology. Bargh and colleagues[110,111] showed that behaviour can be determined by habits and prior attitudes, often without the awareness of the subject. Examples include unconscious imitation of body posture in conversation[112], influence of action, such as speed of walking by implicitly activated stereotypes[111], and environmental determination of strategy choice[113].

The concept of an SAS fits neatly into research by Baumeister and colleagues on self-control, which they argue can be measured by a simple questionnaire that predicts a range of behaviours from resistance to petty temptations, through academic performance, to social and emotional coping capacity[114]. The capacity for self-control is assumed to mediate these effects, based on a system that is limited in capacity and subject to fatigue-like decline[115,116]. The link between working memory and ‘CONATIVE PSYCHOLOGY’[117] presents an important challenge.

Fractionating the executive. It could be argued that the SAS is little more than a homunculus, the little man taking all the important decisions. I would agree, but regard the homunculus as offering a useful scientific strategy, provided we accept that the homunculus defines the problem area, but is not the solution. This requires that we attempt first to specify the processes attributed to the homunculus, and then to explain them[118,119].

I began by postulating the capacities that are needed by any attentional controller, namely to focus, to divide and to switch attention, together with the need to connect working memory with LTM[119]. We made some progress in isolating the capacity to divide attention. We chose two tasks that demand very different peripheral processing, namely auditory digit span and visuomotor tracking, and we titrated the level of difficulty for each subject to a standard level of performance. We then tested simultaneous performance. We found that patients with Alzheimer’s disease were clearly impaired in contrast to normal elderly people, whose capacity for dividing attention was not reliably poorer than for young subjects[120,121].

Our three-part model for working memory encountered problems when trying to address the interaction with LTM. These problems stemmed from our simplifying assumption that the executive was a purely attentional system. This assumption was challenged by a densely amnesic but highly intelligent patient who, despite impaired LTM, showed normal immediate memory for passages of prose comprising some 25 idea units, and extending well beyond the capacity of the loop or sketchpad[122]. Our model also lacked a system whereby ‘chunking’ could occur, allowing information in LTM to supplement immediate serial recall. Chunking results in an immediate memory span for

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McDougall proposed the term ‘conative’ to denote the activity of mental striving or the will, as opposed to cognitive and affective or emotional processes.

sentences of about 15 words, compared to five or six unrelated words. Finally, our model had no mechanism for allowing the phonological and visuospatial subsystems to interact[123], and offered no mechanism for the role of working memory in conscious awareness, which is assumed to depend crucially on working memory[124].

To account for these and other issues, a fourth component was proposed — the episodic buffer[125]. This is assumed to be a limited capacity store that binds together information to form integrated episodes. It is assumed to be attentionally controlled by the executive and to be accessible to conscious awareness. Its multi-dimensional coding allows different systems to be integrated, and conscious awareness provides a convenient binding and retrieval process (FIG. 5).

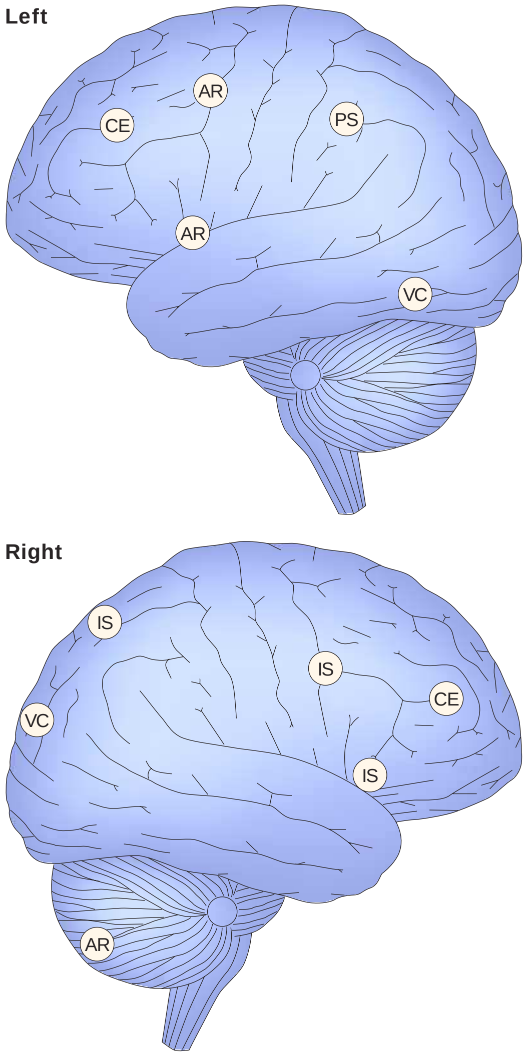

Figure 6 | **A tentative mapping of the working memory model components onto the brain.** The functions associated with each component are not meant to represent the only functions that are served by the associated brain regions, nor are these labels supposed to represent all brain regions associated with a particular function. The central executive (CE), for example, is likely to engage multiple brain regions in a functionally coherent network, including dorsolateral prefrontal cortex. AR, articulatory rehearsal; IS, inner scribe (spatial rehearsal); PS, phonological store; VC, visual cache (storage). Modified, with permission, from REF. 29 © (2001) Psychology Press. Anatomical image adapted, with permission, from REF. 183 © (1996) Appleton & Lange.

The buffer is therefore regarded as a crucial feature of the capacity of working memory to act as a global workspace that is accessed by conscious awareness along the lines suggested by Baars[126,127] (neuropsychological support for such a system is reviewed by Dehaene and Naccache[128]). The buffer was presented as an entirely separate subsystem, but could be regarded as the storage component of the executive. This proposal differs from related proposals[4,129] in assuming that long-term information is downloaded into a separate temporary store, rather than simply activated in LTM. It therefore emphasizes the capacity of working memory to manipulate and create new representations, rather than simply activating old memories. The concept of a common unified store has the further advantage of making the multicomponent model more compatible with approaches to working memory based on individual differences, which have emphasized executive processes rather than subsystems such as the loop and sketchpad (BOX 1).

Anatomical localization of working memory. Studies based on lesion location in patients and neuroimaging in normal subjects indicate that the three basic components of working memory are localized in different brain regions (FIG. 6). The case is most clear-cut for the phonological loop, for which lesion studies have indicated the involvement of the left temporoparietal region[19,130,131]. Subsequent neuroimaging studies have reinforced this conclusion, identifying BA 40 as the locus of the storage component of the loop, and Broca's area (BA 6/44) as involved in the rehearsal component[132–135]. Vallar and Papagno[19] review the neuropsychological evidence for the anatomical localization of the phonological loop, while Smith and Jonides[136] review the neuroimaging evidence. A direct comparison of phonological and visuospatial working memory[137] identified visuospatial working memory as primarily localized in the right hemisphere, in agreement with earlier lesion studies[85,138,139]. Other areas that were broadly analogous to the left hemisphere activation of verbal working memory, namely right inferior parietal cortex (BA 40), right premotor cortex (BA 6) and right inferior frontal cortex (BA 47), were also involved, although there was also activation in the anterior extrastriate occipital cortex (BA 19), which Kosslyn *et al.*[140] have suggested is associated with visual imagery[137,141]. Finally, neuroimaging studies are beginning to throw light on the nature of rehearsal processes in spatial working memory, a topic that has proved difficult to tackle using purely behavioural methods[142].

A number of studies have produced evidence for a separation between spatial and visual or object coding, analogous to the 'what' versus 'where' distinction in visual processing[88,143,144]. In general, neuroimaging studies tend to support the claim that a dorsal stream processes and stores object information, with spatial coding depending on the inferior parietal cortex[87,145].

Lesion studies and functional neuroimaging have provided extensive evidence for an association between executive functioning and the frontal lobes[107,136,146]. A commonly used measure of executive function is the N-back task, in which subjects are presented with a continuous stream of items and are instructed to press a key when they detect a repetition at a specified delay. For a delay of $N = 0$, a sequence such as 7, 9, 3, 1, 1 should evoke a response. The overall load can be increased, typically going up to $N = 3$, for example 7, 9, 3, 1, 9. This difficult task evokes bilateral dorsolateral prefrontal (BA 9/46), inferior frontal (BA 6/44) and parietal (BA 7/44) activation that increases with load[147,148]. There is also evidence for bilateral activation in the dorsal frontal regions when subjects are required to produce a random sequence of digits or key presses[149,150], a task that is known to be executively demanding[151].

There have been extensive attempts to associate different executive processes with specific anatomical locations. This is proving to be a challenging task, with different attempts to summarize existing data producing different conclusions[29,107,152]. For example, D'Esposito *et al.*[153] identified a dorsolateral prefrontal area that was assumed to be involved when two tasks had to be performed simultaneously. However, Klingberg[154] found no such area when subjects were combining two other tasks, whereas other studies have found that dorsolateral activation was reduced by the requirement to perform a concurrent task[155,156]. It seems likely that these results reflect changes in strategy in response to the additional demand. The problem of adequately controlling strategy in imaging studies is important but, I suspect, frequently underestimated. Purely behavioural studies typically use a series of experiments to rule out the possible strategic interpretations of the data, an approach that might be seen as impractically expensive in neuroimaging. It is to be hoped that this crucial variable will increasingly be studied and controlled.

What else is needed for a theory of working memory?

Clearly, there is need for a closer link between research on the phonological loop and work on language perception and production, and between work on the sketchpad, on visual processing and on motor control. In the case of the central executive, there is a clear need to relate it to the extensive work that exists on executive control — much of it being concerned with analysis of frontal lobe function. The proposed link between working memory and conscious awareness also represents a lively and exciting interface.

There is, however, still a paucity of research on what drives the system. The conative, emotional and motivational control of working memory is crucial, but largely ignored. The multi-component working memory model has a concept of information, but no equivalent to Freud's concept of mental energy, nor indeed to the concept of arousal. Without this the system is clearly incomplete. Damasio[157] makes this point cogently, principally using neuropsychological evidence both from adynamic patients who are essentially cognitively inert rather than intellectually impaired, and from patients with frontal lobe damage, who can show apparently normal cognitive capacity coupled with a total inability to make sensible life decisions. Damasio suggests, as do the philosopher Hume[158] and the social psychologist Lewin[159], that it is useful to conceptualize action as ultimately steered by emotion. This process operates indirectly through learning, which associates positive or negative valence to objects, actions and goals.

Our behaviour is clearly determined not by simple chains of cause and effect, but rather by a range of controlling factors that operate simultaneously at many different levels, often implicit, but sometimes explicit. The multi-level nature of the control of action was observed in the nineteenth century by Hughlings-Jackson[160], and emphasized in the twentieth century by Craik[161] and Broadbent[162]. An excellent recent review of the evidence for the multi-level control of action is provided by Frith, Blakemore and Wolpert[163]. Many levels of control are implicit and independent of working memory. It is, however, only within this broader picture that the role of working memory as an attentionally limited but crucial system for thought, planning and action can be fully understood.

In conclusion, working memory continues to provide a highly productive general theory: human thought processes are underpinned by an integrated system for temporarily storing and manipulating information. The multi-component model that is described here offers one account of its underlying processes.

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