Working memory

ROBERT H. LOGIE *explains what we know so far about the 'desktop of the brain'.*

WHAT were you doing just before you looked at this article? How many other things are currently 'at the back of your mind'? What is 37 times 4? If all Society members are psychologists and some psychologists enjoy real ale, then what can be concluded? Can you close your eyes and then pick up an object in front of you? Without looking back, can you recall the last word of each of the previous five sentences? All of these questions require the use of what is often referred to as 'working memory.'

In its broadest sense, working memory can be thought of as the desktop of the brain. It is a cognitive function that helps us keep track of what we are doing or where we are moment to moment, that holds information long enough to make a decision, to dial a telephone number, or to repeat a strange foreign word that we have just heard.

From these examples, it is clear that the concept is much broader than the more traditional idea of short-term memory that typically refers to temporary retention of words, letters or numbers. Working memory, then, encapsulates on-line cognition in both laboratory tasks and in our everyday lives.

There is fairly widespread, although not universal, agreement among researchers that working memory is a useful concept, and interest in its characteristics has grown dramatically in the last few years. The result is something of a debate as to its characteristics (Miyake & Shah, in press; Richardson *et al*., 1996), but I will focus on one particularly successful theory that has been developed largely in Britain and was inspired by the work of Alan Baddeley and Graham Hitch (Baddeley & Hitch, 1974; Baddeley, 1986).

The theory offers an attractive level of simplicity coupled with success in accounting for many laboratory and everyday demands on moment-to-moment cognition. It has also helped the interpretation of a range of cognitive deficits following brain injury or brain disease.

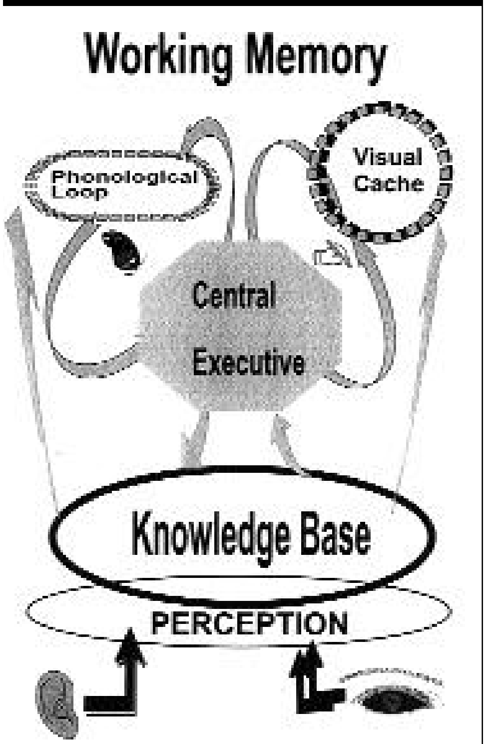
One version of this theory is illustrated in Figure 1 (adapted from Logie, 1995). A key feature of the model shown in Figure 1 is that it contradicts the typical view, in most contemporary introductory psychology textbooks, of short-term memory or working memory as the gateway between perception and long-term memory. The reasons for this change should become clear as the article progresses.

Also immediately apparent from the figure is that working memory comprises a coherent collection of specialised cognitive functions. One group of functions enables temporary storage of the visual appearance of objects and scenes (the visual cache), a second group likewise offers temporary retention of verbal material in terms of sounds or 'phonology' (the phonological loop), while a third offers a co-ordinating executive function which enables the conscious manipulation of information (central executive). All of the components draw on prior knowledge (the 'knowledge base') and on the products of moment-to-moment perception (interpreted via the knowledge base).

The model as a whole is derived from experimental work with normal adults and children, from studies of individuals who have suffered brain damage, from computational modelling, and from recent work using brain imaging techniques.

I will start with a description of what might be some basic requirements for a respectable theory of working memory. This will be followed by a series of illustrations as to how features of the theory outlined in Figure 1 have been used to explore and account for a range of laboratory and everyday cognitive tasks. There will then be a brief discussion of the link with our prior knowledge and expertise before reflecting on the 'state of the art' in this aspect of psychological science.

FIGURE 1



Basics of working memory

Clearly, there are some basic features of a usable working memory. One such feature is its limited capacity. Therefore, only some of our immediate past experience is retained, with the selection based at least in part on task demands. However, despite its limited capacity, working memory has to deal with the products of perception from vision, hearing, taste, smell and touch.[1]

An additional feature is the temporary nature of working memory. This is essential for updating moment to moment, and to avoid crowding our mind with irrelevant information. Nevertheless, it is useful to be able to extend the retention of crucial information when necessary.

The use of the descriptor ‘working’ implies that this is not simply a passive, temporary deposit box for the left luggage of perception (as was one suggested role for the old concept of short-term memory). The contents of working memory can be combined with stored knowledge and manipulated, interpreted and recombined to develop new knowledge, assist learning, form goals, and support interaction with the physical environment.

The theory of working memory outlined in Figure 1 offers a conceptual tool with which to understand the nature of the mental apparatus and of the activity that might support at least some of its basic features.

Visual appearance and location

Try the following experiment. Arrange a few small objects randomly on the table in front of you and then close your eyes. With your eyes shut, choose one of the objects then reach out and try to pick it up. Few people would have difficulty in performing this task, but to do so clearly requires some form of memory for the objects and their location in relation to your hand and body.

Likewise, it is not difficult to describe, from memory, many of the core features of a scene that we have glanced at a few moments before. Nor is it overtaxing mentally to count the number of doors in your house by recalling a few details of the layout of each room.

One way to account for this form of mental ability is to suggest that we have a temporary memory that can hold information about where objects are and what those objects are, thereby allowing us to guide hand and arm movements to the correct location and to pick up the objects in the absence of vision.

This ability is highly adaptive, in that it allows us to recall the location of objects in our immediate environment that are not currently in view (e.g. behind us, occluded by larger objects, or in the dark), and to recall those locations when we change our location or orientation. We can still remember the layout if we turn around or leave the room.

This temporary memory also allows us to recall and describe the physical appearance or layout of familiar environments, such as the inside of our living room or the main square of our home town. The details are drawn from our knowledge base and become available in the temporary memory for the period that the task requires.

Some precise details may be missing, but we could normally describe global features of our home such as the position of doors, windows and major items of furniture, or the main buildings in the town square. We can even extract from these memories details that we had not previously made explicit, such as how many seats there are in our home; and we can use working memory to imagine what the layout of the room would be like if the furniture were rearranged.

Therefore, working memory not only holds information about our immediate environment, it also allows us to generate new information based on our existing knowledge of familiar environments in which we are not physically present.

But note too that the material in working memory is meaningful. That is, the contents of working memory cannot be simply the intermediate products of perception on their way to long-term memory: the information has been subject to interpretation by our stored knowledge and past experience before it reaches working memory. Hence the suggestion in Figure 1 that the processes of perception allow the activation of stored knowledge that is then stored and manipulated in working memory.

Thinking of these mental events in the context of Figure 1, existing knowledge about familiar environments would be activated and made available to the visual cache. Information relevant to our task in hand would then be manipulated within the executive that draws on the contents of the visual cache as and when necessary. Similarly, recently experienced information about our immediate environment could be held in the visual cache, helping to direct our movements and our interaction with objects in that environment.

Mental discovery

Of the characteristics of working memory, mental manipulation and the development of new knowledge are among the most intriguing. They are the focus of a developing research area that is sometimes described as mental discovery (Roskos-Ewoldsen *et al*., 1993). The tasks that are employed in this research are ideally suited also to illustrate why working memory is so effective — by being a bailiwick of specialised functions, rather than a general-purpose memory and processing device.

Try to imagine a circle, a square, a rectangle and two examples of the letter ‘V’. Now mentally move around the images of the shapes, and without the use of any external aids such as pencil and paper, try to mentally construct a recognisable object that includes the letters and all three shapes. You can rotate, expand or shrink the items but do not change their basic shape (e.g. a circle is a circle, not an oval).

Once you have mentally constructed a recognisable object that incorporates as many of the shapes as possible, try drawing it. Each of you will probably have come up with a different object. There is of course no definitive answer, but one possible outcome is shown at the end of this article in Figure 2.

For most of us, it would not have been obvious beforehand that these shapes could be put together in the way that each of us has devised. That is, working memory can be used for mental discovery of new knowledge derived from previously stored information about simple shapes to which are applied some mental operations.

The use of mental images leading to discoveries figures prominently in reports from highly creative individuals such as Poincaré or Mozart (Vernon, 1970). Although not everyone can use imagery this effectively, the ability to make more modest mental discoveries appears to be a basic characteristic of normal human mental equipment (Finke & Slayton, 1988; Anderson & Helstrup, 1993; Reisberg & Logie, 1993).

The task neatly illustrates the use of several characteristics of working memory.

In the context of the model in Figure 1, when you read the shape names above (circle, rectangle, etc.), the phonology for those words is activated from the knowledge base and made available to the phonological loop. This information would decay from the loop after a few seconds, but is retained by rehearsal — repeating the words mentally without overt speech.

As the phonology becomes available, so too the names activate our knowledge of the geometric properties and appearance of the shapes. This information is held within the visual cache, from which it would decay unless maintained, perhaps by repeated mental redrawing of the shapes.

Stored knowledge about how to mentally manipulate shapes (possibly derived from past experience of observing the physical movement of similar shapes) also becomes available to the central executive. Further information about shape name or shape form is drawn into the process of mental manipulation as the cognitive task progresses.

Partial combinations (e.g. the circle, square,V) can be stored in the visual cache, perhaps as a clock face, while the shapes of the other letter V and the rectangle are imagined. These shapes are then combined with the stored partial construction.

Of course, this is very far from an account of creativity, but it does demonstrate how a theory of working memory can be used to understand some of the mental processes that are involved in mental discovery (Pearson *et al*., 1996; Pearson *et al*., in press).

Memory span, counting and language acquisition

Thus far, I have said very little about the more verbally oriented functions of working memory. At one level, these can be seen primarily as a means to store phonological properties of words for brief periods. Yet it turns out that the characteristics of this temporary memory for words — the phonological loop — have significant implications for a wide range of everyday activities. Any activity that requires retention of a verbal sequence such as remembering a new telephone number long enough to dial it, repeating a foreign word or counting objects would rely on this aspect of working memory.

There is now a large literature on this topic suggesting that verbal temporary memory is closely linked with the speech system. So, for example, immediate memory span for digits (such as a telephone number) is severely disrupted if the experimental participant is required to repeat aloud an irrelevant word, such as ‘the the the’— a technique known as articulatory suppression.

Moreover, sequences of words that take longer to say, such as ‘hippopotamus, university, parliament’, are more difficult to remember than are sequences of short words, such as ‘zebra, school, policy’ (Baddeley *et al*., 1975). Closely linked to this finding is the observation that people who can speak quickly tend to have longer digit spans than do people who speak more slowly (Nicolson, 1981).

This link between speaking rate and memory span has important practical implications. For example, Ellis and Hennelley (1980) observed that digit span in Welsh-speaking children was poorer than in English-speaking children. This was attributed entirely to the fact that the words for digits in Welsh take longer to pronounce than do the digits in English.

Similar results have been reported showing shorter digit spans in Italian, where again the words for digits take slightly longer to pronounce than in English (Della Sala & Logie, 1993), and longer digit spans in Chinese where digit words are very short (Stigler *et al*., 1986). In other words, digit span is language specific, and we should be cautious when interpreting digit span scores across languages and cultures.

In terms of Figure 1, overt speaking rate appears to act as a constraint on the rehearsal rate of the phonological loop rehearsal component (indicated by the ‘mouth’ and the looped arrow in the diagram). Longer words take longer to rehearse, therefore the information in the phonological loop begins to decay before it can be reactivated by rehearsal of the items.

A second important application for working memory is in counting and mental arithmetic. For example, when counting we have to keep track of where we are in the counting sequence at any one time. If we are counting objects, such as coins or number of events, we continually have to update our mental record of where we are in the counting sequence. If we are counting an array of objects, such as words on this page, then we have in addition to keep track of which words have been counted and which have not. This is particularly important if the items are scattered randomly in front of us.

Some years ago, Alan Baddeley and I (Logie & Baddeley, 1987) examined whether the working memory theory could shed any light on how normal adults accomplish such tasks. We asked participants to repeat aloud an irrelevant word (articulatory suppression) while they were counting a series of flashes on a computer screen.

Because we already knew that articulatory suppression affects verbal working memory, we were interested to find out whether normal counting would also be affected. It would be affected if the phonological loop were crucial to the counting process.

Articulatory suppression had a dramatic effect on counting. Participants rarely achieved the correct total, although they could do so if they were not repeating an irrelevant word. The disruption did not arise because participants had to do two things at once, because asking these same people to repeatedly tap their hand on the table or presenting them with random words or numbers had virtually no effect on counting. It was the requirement to generate repeated speech that was crucial for the interference to appear.

Therefore, mentally repeating the numbers is crucial for keeping track in a counting task, and this mental repetition comprises the subvocal rehearsal component of the phonological loop.

Given that the phonological loop system had been shown to provide an explanation for important aspects of verbal immediate recall, it appeared that the system could also enable the process of keeping track moment to moment of where we are in a counting sequence.

More recent work has shown that a similar account can be given for mental arithmetic, particularly for sums such as 5 + 3 + 6 + 8 + 2 = ?, in which a cumulative total is repeatedly updated (Logie *et al*., 1994). Each tie total is updated, it is repeated subvocally, and this capitalises on the memory function of the phonological loop.

Clearly, a large part of mental arithmetic relies on a knowledge base of known solutions (McCloskey *et al*., 1991), but mental rehearsal within the phonological loop appears to offer an account of how we keep track of intermediate totals as we progress through a sum, as well as where we are in a counting sequence.

The phonological loop component of working memory has proved useful in studies of language acquisition in young children. Susan Gathercole, Alan Baddeley and others (e.g. Gathercole & Baddeley,

1989) have shown that young children's ability to repeat a series of nonsense words at age 3 or 4 predicts their language ability several years later.

This suggests that the ability to repeat an unfamiliar speech sound (a feature of the phonological loop) is important for acquiring vocabulary and other language skills, both in young children and in adults learning a second language.

The loop has also been found invaluable in interpreting the pattern of difficulties encountered by brain-damaged patients who show deficits of one component of working memory while having other components intact (for a review, see Della Sala & Logie, 1993).

Recent developments in neuroimaging techniques offer further converging evidence for the concept of a phonological loop that has both a memory store and a rehearsal system. Paulesu *et al*. (1993) used positron emission tomography (PET) to measure regional Cerebral Blood Flow (rCBF) during a series of tasks that systematically varied whether participants had to store a series of letters or mentally repeat the letter sounds.

By contrasting rCBF observed during the performance of each task, Paulesu *et al*. identified mental rehearsal of letter sounds with an area of the brain known as Broca's area. This area is more commonly associated with aspects of speech production, but appears also to be involved in 'mental speech' or the rehearsal component of the phonological loop. The letter memory task was associated with an area known as the supramarginal gyrus.

This pattern supported the idea that the phonological loop comprises separate components for phonological storage and for mental rehearsal.

Long-term working memory

In the spirit of the examples given above, working memory should offer temporary memory for immediate past experience, plus some means to mentally represent the immediate environment and to manipulate and continually update the contents of that mental representation. Also it should support the acquisition of new knowledge, problem solving and decision making (for recent reviews, see Logie & Gilhooly, 1998). However, none of this can happen in isolation from past experience.

Knowledge accumulated over our lifetime is clearly available to each of us. When we think of castles in Scotland, colleges in Cambridge, or television soap operas, our accumulated knowledge becomes readily available to us.

Fans of Scottish historical monuments will immediately recollect details of visits to Balmoral or Crathes Castle, and questions on this topic can be answered with consummate ease. A knowledge of Cambridge likewise allows us to bring to mind images of St John's, King's, Trinity and so on.

Having activated such knowledge, we can then manipulate it and extract novel information that had not been explicitly stored away, such as whether King's College Chapel in Cambridge is larger or smaller than Crathes Castle in Aberdeenshire. Similar questions about television soap operas would bring nothing to mind for some, or richly endowed memories of plots and characters for others.

Ericsson and colleagues (e.g. Ericsson & Delaney, 1998) distinguish between a short-term working memory — on which I have focused thus far — and a long-term working memory that accounts for the ease with which we can access highly familiar stored knowledge. The greater our expertise in a particular domain, the greater is our working memory capacity for information in that domain.

Thus, chess experts can retain details of chess games played simultaneously even when blindfold (Saariluoma, 1995), and avid soccer supporters can remember scores from matches more accurately than can the more casual fan (Morris *et al*., 1985).

Even experience in crime leads to a form of, albeit undesirable, expertise: experienced burglars can remember details in photographs of houses seen a few moments before better than can samples of police officers or householders (Logie *et al*., 1992).

In each case, the expert knowledge allows very efficient coding and retrieval of information within the area of expertise. These memory skills clearly do rely on the short-term working memory, but expertise greatly facilitates activation of relevant information in the knowledge base, and this activated knowledge can offer significant support for the more limited temporary working memory system.

The 'state of the science' of working memory

Within the scope of this article, it is impossible to give a comprehensive coverage of the topic. Working memory has been explored in many more everyday tasks than I have discussed, including language comprehension (e.g. Engle *et al*., 1992), development of cognitive capacity in young children (e.g. Hitch, 1990), and adult reasoning (e.g. Gilhooly, 1998) among others. Indeed, it is difficult to think of many human activities that would not involve working memory at some level.

Developments in the use of computational modelling techniques (e.g. Burgess & Hitch, 1992) and in neuroimaging (e.g. Paulesu *et al*., 1993) allow us to be more confident that the functional model of working memory can be simulated computationally and might have neurological correlates. The computational approach forces us to ask very detailed questions of the specificity of our conceptual theories of working memory. This adds significant theoretical rigour.

But it is crucial to follow the pattern adopted by Hitch and colleagues in coupling the computational modelling with experimental data from human participants. All too often, computational modelling progresses without direct reference to empirically derived data on human cognition.

The neuroimaging approach is extremely valuable clinically, as well as scientifically, in neuropsychology research and in attempts to chart a neurobiological map of cognitive functions. PET and fMRI (functional Magnetic Resonance Imaging) offer compelling evidence to confirm and perhaps refine the existing theories derived from a range of other experimental techniques as well as from computational modelling.

However, it will be interesting to observe the extent to which neuroimaging can *disconfirm* theories of cognition that have been built on a large body of behavioural data from carefully crafted experiments. This cautionary point is perhaps best illustrated by quoting the writings of G.F. Stout[2] (1919), who commented:

> *Even if the brain of a man could be so enlarged that all the members of an International Congress of Physiologists could walk about inside his nerve fibres and hold a conference in one of his ganglion cells, their united knowledge and the resources of all their laboratories could not suffice to enable them to discover a feeling or sensation or perception or idea. (p.16.)*

Recent advances in technology have allowed us to emulate Stout's scenario (if not quite literally) and to suggest that he might have been at least partially wrong. In the spirit of Descartes, we know working memory exists because we use working memory every waking moment of our lives. This subjective experience is coupled with a large body of empirical evidence as to its characteristics.

Now evidence from neuroimaging, in combination with the established empirical literature, gives us a hint as to where in the brain different aspects of working memory might be. This reinforces the role of working memory as a serious and useful scientific concept for understanding the nature of our own cognition.

Notes

[1] In practice, the cognitive products of only vision and hearing have been studied to any great extent.

[2] G.F. Stout was appointed to the Anderson Lectureship and founded the Department of Psychology at the University of Aberdeen in 1896. The first edition of his *Manual of Psychology* was published in 1897.

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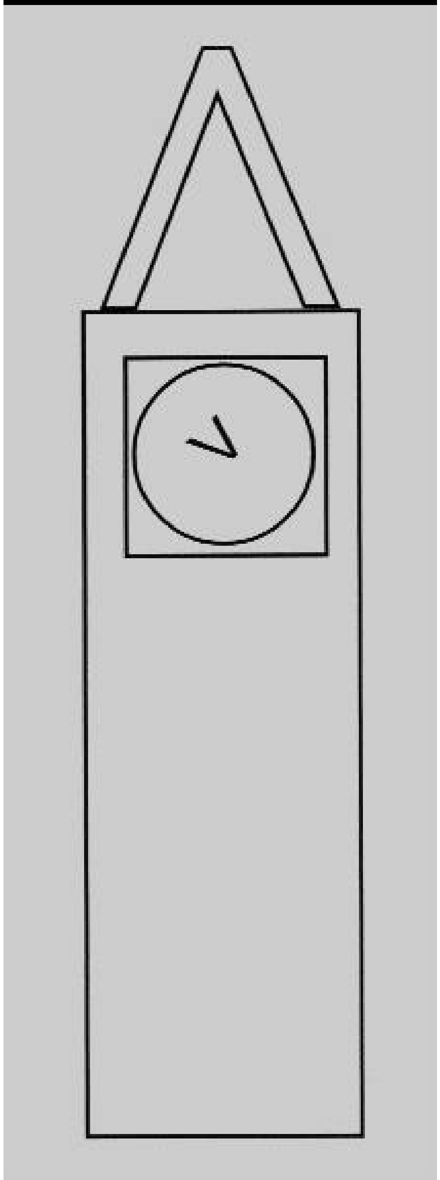
FIGURE 2 A possible mental construction using various given shapes



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