Working Memory

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The term 'working memory' refers to the temporary storage of information in connection with the performance of other cognitive tasks such as reading, problem-solving or learning. It is here conceptualized as comprising a limited-capacity central processor, the central executive, which employs a number of subsidiary slave systems. Evidence for this view is presented, together with a more detailed account of two such systems: the articulatory loop, which stores and manipulates speech-based material, and the visuo-spatial scratch-pad, which is responsible for creating and maintaining visual imagery.

Introduction

Although the term 'working memory' has only gradually achieved popularity, temporary storage in human memory has been an area of active theoretical interest for at least 25 years. It is easy to look back on the area as producing a series of controversies each of which flared into activity only to fade away. But underlying these there is a continuity of development whereby the initial assumption of a unitary memory system was elaborated into a dichotomy between long-term and short-term memory, both of which were subsequently subdivided: long-term memory into semantic and episodic memory (Tulving 1972) and short-term memory into a range of subsystems. Collectively, the latter are called 'working memory', an alliance of separate but interacting temporary storage systems, possibly coordinated by a single central executive component. Although this conception can on the one hand be seen as a departure from the classic concept of short-term memory, many of the components and characteristics of working memory bear a striking resemblance to those of earlier models extending back to Broadbent's influential initial model (Broadbent 1958). Because I believe that it is important to emphasize the continuity, I shall devote the first part of this paper to an overview of the development of the concept of short-term memory into the broader concept of working memory, before going on to outline my own views on the probable structure and function of working memory.

One memory system or two?

Although the possibility of two separate types of memory had been suggested as early as 1883 by Francis Galton, the argument for a functional separation between long-term and short-term memory first achieved prominence through the work of Broadbent (1958), who strongly advocated the dichotomy, and the influential counter-argument by Melton (1963), who defended a unitary concept of memory. This in turn led to a search for empirical evidence for or against the dichotomy. This literature has been reviewed elsewhere (e.g. by Baddeley 1976), but includes the following sources of evidence in favour of a separation between long-term and short-term memory.

1. *Two-component tasks*. A number of tasks yielded data suggesting that they comprised two

memory components, a relatively stable long-term component, and a much more labile short-term component (Glanzer 1972; Peterson 1966; Waugh & Norman 1965).

2. *Neuropsychological evidence.* It has been known at least since the 1940s (Zangwill 1946) that patients suffering from the Korsakoff syndrome exhibit profoundly disturbed long-term learning capacity that may nevertheless be accompanied by a normal memory span, as measured by the ability to repeat back a sequence of digits or words. Milner (1966) pointed out that the classic amnesic patient H.M. also appeared to show a dissociation between immediate memory and long-term memory, while a study by Baddeley & Warrington (1970) examined the performance of a number of amnesic patients on tasks assumed to reflect separate short-term and long-term memory components. The results supported the dichotomy by suggesting normal short-term memory but impaired long-term memory.

Further evidence for neurological dissociation was presented by Shallice & Warrington (1970), who described a patient having the opposite characteristics, normal long-term learning ability, coupled with an immediate memory span of only two items.

3. *Differential coding.* Evidence from the immediate memory span task suggested that short-term memory relied heavily on some form of speech coding, representing the sound or articulatory characteristics of the material but not its meaning. Errors tend to be phonologically similar to the correct item (Conrad 1964), while sequences of phonologically similar items are hard to recall accurately (Baddeley 1966*a*).

When the task required long-term learning, however, the pattern was quite different, with coding based on meaning becoming important and phonological similarity ceasing to be a significant factor (Baddeley 1966*b*; Kintsch & Buschke 1969; Sachs 1967).

The modal model

By the late 1960s, this and other sources of evidence seemed to point clearly to a dichotomy between long-term and short-term memory. A great many competing models of short-term memory were developed, often expressed mathematically and attempting to make precise predictions, although typically of a very limited set of experimental data. The models tended to have much in common, and could be regarded as variants on a single underlying theme, which Murdock termed the 'modal model'. The most influential of these was that presented by Atkinson & Shiffrin (1968). This was essentially a development of Broadbent's original model (Broadbent 1958), and, like it, distinguished two kinds of short-term system: a range of brief sensory stores capable of operating in parallel, which in turn feed into a unitary short-term memory store of limited capacity. The latter was assumed to function as a working memory needed for holding and manipulating information and for transferring it to the more permanent long-term memory system. Transfer was assumed to be automatic but relatively slow. Consequently, learning required maintaining information in short-term memory. The longer the maintenance the greater the degree of transfer and the greater the amount of learning. The short-term store was assumed to have access to a number of *control processes* or strategies for manipulating information. Although a range of such processes was postulated, empirical investigation was largely confined to the simple process of subvocal rote rehearsal.

PROBLEMS WITH THE MODAL MODEL

In the early 1970s, the amount of work on short-term memory began to decline; the reasons for this decline are various, but probably included the growing complexity of empirical data in the field: new techniques had begun to proliferate, and the problems of mapping the results of any technique onto a single underlying theoretical structure became progressively more complex. At the same time it became increasingly clear that certain phenomena were difficult to fit into the modal model. These included the following.

1. *Neuropsychological evidence.* If short-term memory is necessary for long-term learning, then why should patients such as those studied by Shallice & Warrington (1970), whose short-term learning ability is clearly impaired, show normal long-term memory?

2. *Dissociation between short-term memory and long-term learning.* A number of studies observed that repeated rote rehearsal may lead to very poor long-term retention unless some form of deeper semantic processing or elaboration takes place. The most influential experimental demonstration of this was offered by Craik & Watkins (1973), but a more expensive though inadvertent demonstration was provided by the B.B.C., who attempted to use saturation advertising to familiarize its audience with a change in radio wavelengths. Bekerian & Baddeley (1980) investigated the effectiveness of this campaign, which involved presenting the information in repeated announcements, statements and jingles on radio programmes over a period of weeks. We were able to estimate that subjects must have heard the information in excess of 1000 times, and yet retained virtually none of it, confirming the observation of Craik & Watkins that repetition does not guarantee learning.

3. *Long-term recency effects.* The recency effect in free recall is probably the most characteristic example of a short-term component of a two-component task. The suggestion that the recency effect reflects the contents of a short-term store ran into difficulties, however, with the discovery of recency effects extending over long periods of time. These range from several minutes under laboratory conditions (see, for example, Tzeng 1973) to days or even weeks in rugby players asked to remember which teams they had played against (Baddeley & Hitch 1977).

Other evidence against the necessary association of recency with short-term memory is reviewed by Baddeley & Hitch (1976) and by Watkins & Peynircioglu (1983). Recency has so far been investigated primarily as a limited laboratory phenomenon, of theoretical but not practical significance. I myself suspect that recency represents a very basic and important aspect of human memory concerned with the vital question of maintaining orientation in time and space. However, although it seems a simple phenomenon, we still do not have a good general model of recency, or indeed an adequate understanding of the similarities and differences between long-term and short-term recency effects.

ALTERNATIVES TO THE MODAL MODEL

Levels of processing

As the modal model began to lose favour, it was succeeded in popularity by a theoretical framework presented by Craik & Lockhart (1972), who termed their approach *Levels of processing*. This approach changes the emphasis of the modal model away from structure to processing, and postulates that the more deeply a subject processes a stimulus, the more durable will its memory trace be. However, although the concept of levels of processing offers a useful rule of thumb for predicting the effects of differential coding in long-term memory, it is open to a number of theoretical criticisms (Baddeley 1978), and has said little about the nature of working memory; hence it will not be further discussed here.

Working memory

Although it had been widely assumed that short-term memory functioned as a temporary working memory, until recently empirical evidence for such a view was remarkably sparse. Indeed, patients such as those who appeared to have grossly defective short-term memory, studied by Shallice & Warrington, often seemed to encounter very few practical problems in coping with the information-processing demands of their everyday life. In the early 1970s Hitch & I decided that we would explore this point further by attempting to disrupt the operation of short-term memory in normal subjects, and then observing their performance on a range of information-processing tasks.

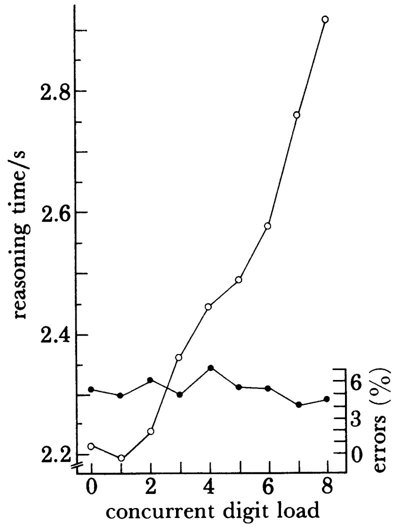

Figure 1. Speed and accuracy of verbal reasoning as a function of concurrent memory load.

What Murdock called the modal model made two primary assumptions: first, that the system had limited storage capacity, and second, that the digit span task taxed this limited capacity to the full. We therefore presented our subjects with sequences of digits that they were required to maintain by rehearsing aloud while they attempted to perform one of a number of other tasks. These were tasks that might be expected to depend on a limited-capacity working memory, and included learning, comprehension of prose, and verbal reasoning.

One such experiment (Baddeley & Lewis, unpublished), involved requiring our subjects to remember sequences of from one to eight random numbers while performing a reasoning task in which they were to decide whether sentences correctly described the order of two letters. Some sentences were simple such as *A follows B – BA*: (true), while others were made more complex by including passives and negatives (*B is not preceded by A – BA*: true). Our results are shown in figure 1.

As predicted by the working memory hypothesis, reasoning takes longer as the memory load increases. Note, however, first that the effect on latency is clear but not massive, and secondly that accuracy remains at approximately 95% regardless of memory load. Finally individual subjects varied widely, with some showing virtually no effect until the load reached seven or eight digits. Memory load does interfere, implying some overlap of processing with the reasoning task, but even loading the subjects' memory to capacity still leaves them able to reason accurately.

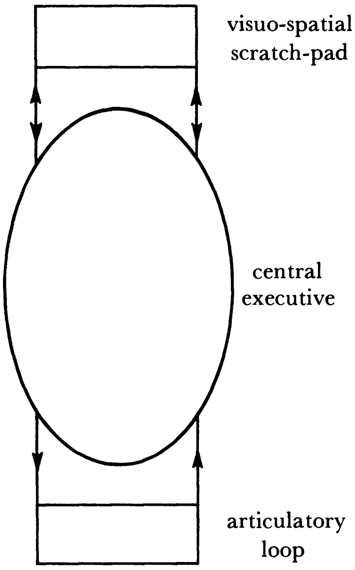

FIGURE 2. A simplified representation of the working memory model.

Comparable results were obtained from studies of learning and of comprehension, and together with the evidence against the simple modal model described earlier convinced us of the need to abandon the assumption of a single unitary short-term memory in favour of a working memory that comprises a central controller together with a number of interrelated subsystems (Baddeley & Hitch 1974). I shall begin by outlining the system briefly before discussing two of the subsystems in more detail. It should perhaps be pointed out that what follows represents my current view of a changing and developing model. As such it differs in some ways from earlier formulations, and will itself be superseded as more is learnt about working memory.

THE CENTRAL EXECUTIVE

A simplified representation of the working memory system is presented in figure 2. This shows two of the major subcomponents of the system, together with the central executive – the core of the system that is responsible for coordinating information from the subsidiary slave systems. The central executive is assumed to function like a limited-capacity attentional system capable of selecting and operating control processes and strategies. It represents the most complex aspect of working memory and the most difficult both to analyse and conceptualize. Consequently we have concentrated on the presumably simpler task of splitting off and studying the more peripheral slave systems, gradually whittling down the functions that we need to assign to the central processor. In this respect, the central executive could, not unfairly, be described as the area of residual ignorance. It is indeed possible that it may ultimately prove unnecessary to assume a central executive if, as for example Barnard (1983) suggests, control is exercised by the interaction of the various subsystems without recourse to a central controller. At present, however, I can see no way of achieving this, and consequently find it useful to retain the concept of a central executive if only as a reminder of the important question of how the whole working memory system is controlled.

Passive and active storage processes

It is assumed that the central executive can take advantage of a number of more peripheral storage systems. Such stores are probably multi-functional, also playing parts in other processes such as perception and speech processing. I suggest that we should distinguish between passive stores, in which information is registered and subsequently either fades or is displaced, on the one hand, and active stores on the other. It is suggested that active storage involves rehearsal, a process whereby the system reads out information from the store and then feeds it back, thereby continually refreshing or updating the memory trace. This is best illustrated by describing the two active slave systems hat we have so far investigated in most detail: the articulatory loop (a.l.) and the visuo-spatial scratch-pad (v.s.s.p.).

The articulatory loop

One of the most striking features of earlier work on short-term memory was the association with speech coding. Indeed, this led to suggestions that short-term memory was synonymous with a subvocal rehearsal system. The working memory concept, on the other hand, restricts phonological coding to one of the subsidiary slave systems, the articulatory loop. The loop is assumed to comprise two components, a phonological input store and an articulatory rehearsal process involving subvocal speech. This relatively simple model is able to account for a large amount of empirical data, including the following.

(*a*) *The phonological similarity effect.* Sequences of consonants with similar sounding names such as *b*, *g*, *c*, *v*, *t*, *p* are harder to remember than dissimilar sets such as *h*, *w*, *y*, *k*, *r*, *l* (Conrad & Hull 1964).

(*b*) *The word length effect.* Memory span decreases with increased word length, and hence the span for monosyllables such as *sum*, *day*, *wit*, *harm*, *peg*, is substantially larger than that for polysyllables such as *university*, *aluminium*, *representative*, *opportunity*, *organization.* Further, the span is a simple function of spoken duration rather than number of syllables, thus words that can be said quickly such as *bishop* and *wicket* are remembered better than words such as *harpoon* and *Friday*. When a subject's span is measured in terms of spoken duration, it works out at approximately 1.5 s, regardless of the lengths of the words (Baddeley *et al.* 1975*b*).

(*c*) *The unattended speech effect.* Memory for visually presented items such as numbers can be impaired by the simultaneous presentation of spoken material that the subject is instructed to ignore. The semantic characteristics of the unattended material are unimportant, with nonsense syllables being as disruptive as words, whereas phonological factors are of significance, with bursts of noise having a much smaller effect than unattended speech (Salamé & Baddeley 1982).

(*d*) *The articulatory suppression effect.* When subvocal rehearsal is prevented by requiring the subject to articulate continually some irrelevant sound such as the word *the*, performance on immediate memory span is consistently impaired. Suppression has the further effect of interacting with the three previous phonological variables. The unattended speech effect disappears, the word length effect becomes insignificantly small, and the phonological similarity effect is abolished when presentation is visual, but not when it is auditory.

The articulatory loop model accounts for these results as follows. It is assumed that the phonological store can be accessed either by subvocal speech, an optional strategy, or directly through auditory speech input, an obligatory process. Phonologically similar items are assumed to lay down similar and hence confusable traces in this store. With auditory presentation, registration in the store is obligatory regardless of whether the subject is engaged in subvocal rehearsal. With visual presentation, such registration occurs *only* if the subject is able to subvocalize the items as they are presented. If this is prevented by articulatory suppression, then the material is not registered in the phonological store, recall is based on other sources of stored information (possibly visual), and no phonological similarity effect occurs.

The word length effect is assumed to be a characteristic not of the phonological store but of the articulatory rehearsal process. Memory span is a function of both the durability of a trace within the phonological store and the rate at which rehearsal can refresh that trace. If unrehearsed, a phonological trace will fade within 1–2 s. Rehearsal reactivates the trace, and consequently if rehearsal can be repeated every 1–2 s, forgetting will be prevented. Memory span is determined by the number of items that can be rehearsed and hence reactivated before the traces fade. Long-duration words take longer to rehearse, and so the number that can be maintained in the 1–2 s available is less than for short words. Articulatory suppression prevents rehearsal, and hence removes the effect of word length.

The effect of unattended speech is assumed to occur because spoken material has obligatory access to the phonological store. Under normal conditions, visually presented items will be recoded phonologically so as to take advantage of this supplementary storage. If, however, the store is corrupted by irrelevant speech, this advantage is minimized. With articulatory suppression, the subvocal transfer of information to the phonological store is not possible, and any disruption of that store by unattended speech has no influence on performance.

The articulatory loop therefore appears to be essentially an input store whose primary function is probable speech perception, which can be transformed at the user's option into an active memory store by means of subvocal rehearsal. It is clear that such rehearsal need not be overtly vocal, but it is less clear to what extent rehearsal requires peripheral articulation as opposed to the running off of more central articulatory programs. An opportunity to investigate this question occurred recently in a study done jointly with Barbara Wilson of the Rivermead Rehabilitation Centre Oxford, of a patient who had lost the power of overt speech as a result of brain damage.

The patient was an undergraduate who had been involved in a car crash that left him, initially, completely paralysed. He subsequently recovered the use of his upper limbs but remained totally unable to speak, his vocalization being limited to an inarticulate inspiratory cry. However, using a Canon communicator he was able to converse by typing out his responses. He was non-aphasic as determined by the Token Test, which requires performing complex instructions, and showed excellent comprehension on both vocabulary and synonym-matching tests.

We explored his immediate memory performance in some detail, being concerned especially with the question of whether he would show any evidence of a functioning articulatory loop. Should the loop be dependent on peripheral articulation, then the patient should perform much as would a normal subject under articulatory suppression. On the other hand, if subvocal rehearsal can be performed entirely centrally, one might expect relatively normal performance. Our results, shown in table 1, indicate first that his memory span is relatively normal, secondly that he shows a phonological similarity effect not only with auditory, but also with visual, presentation. Finally, he shows a clear word-length effect, suggesting that some form of subvocal rehearsal is occurring, and that as with normal articulatory rehearsal, it is slower for longer than for shorter words. Thus the process of subvocal rehearsal appears to be independent of the control of the peripheral articulatory musculature. Broadly comparable results have been obtained by Nebes (1975) and in unpublished work from Milan (G. Vallar, personal communication).

Table 1. Working memory in an anarthric patient
(Baddeley & Wilson (1983).)

	phonological similarity			
			similar	dissimilar
six consonants				
auditory				
correct sequences (%)			70	100
correct items (%)			83	100
visual				
correct sequences (%)			40	60
correct items (%)			72	85
	word length			
			long	short
six words				
auditory				
correct sequences (%)			20	50
correct items (%)			48	65
	sound matching			
regular words				
e.g. pause	paws	√	94%	
sour	sore	×		
irregular words				
e.g. doe	dough	√	96%	
roe	rough	×		

Although the pattern of results from the various studies described is consistent with our simple model of the articulatory loop, a number of puzzles remain. One of these is that although articulatory suppression appears to prevent phonological coding, as indicated by the phonological similarity effect, it does not hamper a subject's ability to judge whether two written words rhyme or not (Baddeley & Lewis 1981). It is very easy to demonstrate a similar effect simply by reading and suppressing articulation. Most people find that they can 'hear' an inner voice despite the suppression. Why this inner voice is not sufficient to sustain rehearsal, or to show phonemic similarity effects, remains a puzzle. Does it represent an auditory image, and if so how is this related to the functioning of the articulatory loop?

A second puzzle concerns the nature of the system in which visually presented material is stored during articulatory suppression. The system's insensitivity to phonological similarity implies that the code is not phonemic in nature. However, the system does appear able to retain order information, whereas the function of the visuo-spatial scratch-pad described below seems to be in maintaining a single spatially organized representation. On the other hand the difficulty in obtaining clear effects of visual similarity in memory for letters makes a simple peripheral visual store seem unlikely, and suggests something rather more abstract or possibly lexical. It seems likely that the nature of the 'inner voice' and the characteristics of this 'visual' store will receive increasing attention over the next few years.

The visuo-spatial scratch-pad

This is the second system that we have explored in some detail. It appears to be specialized for maintaining and manipulating visuo-spatial images, and to resemble the articulatory loop in being essentially an input store with active storage capabilities attributable to the regeneration of memory traces by a process external to the store.

The functioning of the v.s.s.p. is perhaps best illustrated by using a technique initially devised by Brooks (1967) to separate verbal and visual short-term memory. This is illustrated in figure 3, which comprises a matrix of cells, one of which is denoted the starting square. The subject's task is to repeat back a series of statements. In one condition the statements can be recoded into a path through the matrix, and hence remembered as a particular pattern. The pattern can then be recoded back into the original statements for recall. The non-spatial comparison condition is formally equivalent except that the adjectives presented are not suitable for simple spatial encoding, and at the rate at which material is typically presented subjects are forced to remember the sequence by rote. Examples of the two types of sequence are given below the matrix in figure 3. Recalling eight spatially coded statements is about as difficult as recalling six of the non-spatial nonsense sequences. Work by Brooks indicates that the spatial sequences are best retained when presented auditorily, while the nonsense sequences are best retained when presented visually. His interpretation is that representation of the spatial sequences relies on a visuo-spatial coding system that mutually interferes with visual processing of written material, while the nonsense material does not.

		3	4
	1	2	5
		7	6
		8	

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 3. The task for studying spatial and verbal memory coding, devised by Brooks (1967).

Experiments of our own began by exploring an observation made while trying to perform a natural visual imagery task, listening to an American football game on the radio while performing the visuo-spatial task of steering a car down an American freeway. The two tasks seemed to interact, and I hurriedly switched the radio to a music programme. In our laboratory studies we used Brook's task to induce imagery and as an analogue of the driving task, used the traditional psychological apparatus known as the pursuit rotor, in which the subject attempts to keep a stylus in contact with a spot following a circular track. Using this approach, we made the following observations.

1. Tracking caused marked impairment in performance on the spatial memory task, but had no effect on the nonsense task involving rote verbal memory (Baddeley *et al.* 1975*a*, expt 2).

2. When the memory tasks were given priority, the spatial task disrupted tracking much more than did the verbal task (Baddeley *et al.* 1975*a*, expt 1).

3. We carried out an experiment to investigate whether the system was primarily visual or more generally spatial in character by studying the effect on the two Brooks's tasks of a visual but non-spatial secondary task (judging the brightness of a patch of light) and a spatial but non-visual task (tracking the location of a moving sound source while blindfolded, using a flashlight). When the flashlight was on target, the sound changed, providing feedback. Although this task was spatial, because the subject was blindfolded it did not involve the peripheral visual system. Our results showed that imagery was much more disrupted by this latter task than by the visual brightness judgement, which tended to have a greater effect on the nonsense memory task. This and other data from other investigators suggest that the system is primarily spatial rather than visual in nature (Baddeley & Lieberman 1980).

4. A series of experiments explored the role of imagery in memory for words, using the concurrent tracking task as a source of disruption. Results suggested that spatial imagery mnemonics such as the classic location mnemonics rely on the v.s.s.p. and are disrupted by concurrent tracking. On the other hand, the general tendency for words of high imageability to be better remembered than abstract words is unaffected by concurrent spatial tracking, suggesting that this effect may reflect the manner in which such words are registered in semantic memory, rather than the active strategy of the subject (Baddeley *et al.* 1975*a*; Baddeley & Lieberman 1980).

It was suggested that the articulatory loop system is an active one, capable of maintaining information because it combines a passive phonological store with active articulation that permits internal input to the store and hence refreshment of the memory trace. Given that the visuo-spatial scratch-pad also appears to function as an active store in which information can be maintained, the question arises as to the nature of the process responsible for maintaining the trace. One suggestion that has frequently been made is that eye movements are involved in setting up, maintaining or retrieving visuo-spatial images (see, for example Hebb 1968). On the whole, however, evidence for this view is sparse, coming mainly from attempts to monitor eye movements while subjects are instructed to form visual images, and typically producing weak or conflicting results (see, for example, Brown 1968; Hiscock & Bergstrom 1981). This approach would be analogous to studying the articulatory loop by using electrodes to monitor the articulatory muscles. Such a technique has indeed been used to study subvocal speech, producing effects of varied magnitude and reliability, and revealing little about the underlying processes. Since our subject who has no control over his articulatory muscles nevertheless appears to have perfectly adequate inner speech, it seems unlikely that monitoring the activity of the speech musculature will give a very adequate indication of the articulatory loop.

A more fruitful technique in studying the articulatory loop is suppression. Is it possible, then, that eye movements might suppress spatial coding? Unpublished work by Nancy Vye of Vanderbilt University provided some evidence that optical nystagmus might disrupt the use of visual imagery, and so we decided to explore the effect on the Brooks imagery task of seating our subjects in a revolving chair and rotating them vigorously (Idzikowski *et al.* 1983). The results of this somewhat draconian procedure were rather disappointing. Although clear post-rotational nystagmus was produced, impairment in performance was slight and tended to be if anything greater for the nonsense sequences than for the spatial, the opposite of the prediction of the eye movement hypothesis.

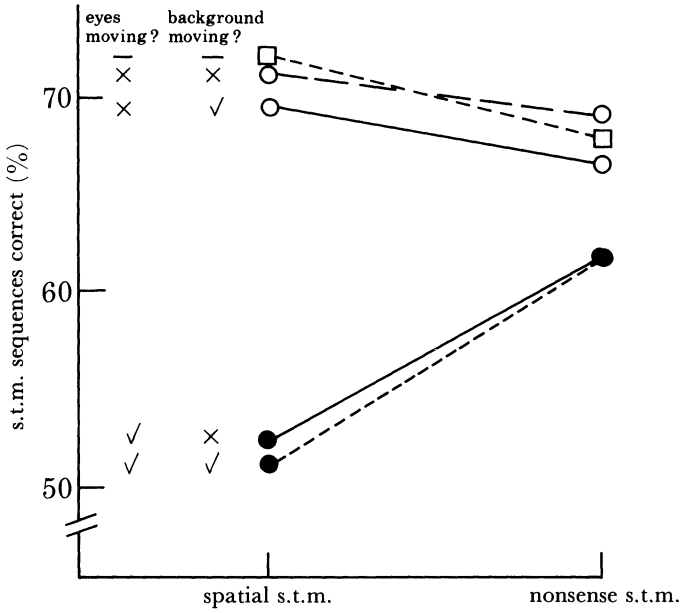

Figure 4. Effect of movement of the eyes and the background on the use of visuo-spatial imagery. ×, Eyes fixed; √, eyes moving; —, eyes free. (Data from Idzikowski *et al.* (1983).)

Nevertheless, arguing that the crucial rehearsal-controlling process may not be the eye movements themselves but rather the central system involved in their voluntary control, we decided to press on. We therefore opted for a technique more closely analogous to articulatory suppression, in which the subject actively tracks with his eyes a target following a sinusoidal path on the visual display unit of a computer. We had a second condition in which the target remained stationary, and the background moved sinusoidally, allowing us to determine whether any observed effects were due to the movement of the eyes, or simply to erasure of the image by the movement of the retinal image. Finally, to be certain that fixating a stationary target was not in itself disruptive, we included a free condition in which subjects could move their eyes as much or little as they chose. Despite the complex design, the pattern of results was relatively simple. As figure 4 shows, movement of the eyes disrupted performance on the spatial, but not the nonsense, task. However, requiring the eyes to remain stationary, or moving the background, had no substantial effect on performance.

In conclusion, the visuo-spatial scratch-pad appears to comprise a store linked with a rehearsal process, in this case that used voluntarily to control eye movements.† As with the articulatory loop, the crucial feature appears to be the central controlling system rather than the peripheral effector system. The imagery system seems to be spatial rather than purely visual in nature, although this may simply reflect the fact that we have so far only succeeded in finding spatial disruption of tasks, attempts to produce equivalent disruption by using nonspatial pictorial tasks being on the whole much less successful (Baddeley & Lieberman 1980).

Of the many questions that remain to be answered in the area of visual working memory, several seem likely to reward further investigation. These include the relation between the visuo-spatial scratch-pad and (i) visual short-term memory (see Phillips, this symposium), (ii) the perception and retention of objects, scenes and faces (see Bruce, this symposium), and (iii) the non-phonological 'visual' short-term store involved in remembering visually presented letters described in the previous section.

Applying the concept of working memory

I have so far attempted to illustrate how the concept of working memory can be broken down into subcomponents, and these in turn analysed in some detail. However, the essence of the concept of working memory lies in its concern with the use of temporary storage to perform such important cognitive tasks as reasoning, comprehension and learning. Consequently, in parallel with the more detailed theoretical analysis of subcomponents, we have been concerned to use what we know of working memory to help understand other more ecologically relevant information-processing tasks. Unfortunately, space does not permit a detailed account of such applications. These involve, in our own case, the study of both fluent reading and learning to read (Baddeley 1978, 1982; Baddeley & Lewis 1981; Baddeley *et al.* 1981). The concept of working memory has also been useful in approaching the breakdown of normal cognitive functioning, including the nature of the deficit in patients suffering from impaired short-term memory (Vallar & Baddeley 1983) and of the reading problems encountered in developmentally dyslexic boys (Baddeley *et al.* 1982). In addition, the concept of working memory has proved useful in analysing the cognitive processes involved in simple arithmetic (Hitch 1978), and, as the next paper will show, in understanding the development of working memory through childhood.

Conclusion

The concept of working memory is a very general one, replacing the idea of a single unitary short-term memory with an alliance of subsystems. We have as yet made progress in analysing only two of what may prove to be a number of such component systems, and have only begun to tackle the important question of how the information from such systems is coordinated. None the less, I think we can claim to have had some success in teasing out the details of at least two of the systems, the articulatory loop and the visuo-spatial scratch-pad. Furthermore, the

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† It should be pointed out that although we have used eye movements as our means of disrupting imagery, it may be the system for visual *attention* that is disrupted rather than that for directing the eyes. Posner (1980) has shown that although these are normally highly correlated, they can be experimentally separated.

concept of a working memory appears to conceptualize the advances we have made in the laboratory in such a way that they can be applied to ecologically relevant cognitive tasks such as reading and arithmetic. Finally, I would like to claim that work in this area has been cumulative. Although the fashion for carrying out work on short-term and working memory has oscillated widely during the last 25 years we have made genuine steady progress. Empirical work such as that of Conrad (1962) and theoretical work such as that of Broadbent (1958) continue to be influential; we know considerably more about the phenomena and have more elaborate models, but these are essentially developments of the earlier approach rather than completely new departures.

One factor that is different in emphasis from the 1960s, however, is the blurring of the distinction between memory and other cognitive processes. It seems likely that working memory uses components of many other cognitive systems, notably those involved in perception and action in general, and speech perception and production in particular. This inevitably means that we are unlikely to understand working memory fully until we understand perception, decision and thought. Thus it seems likely that the topic of working memory will provide challenging and important questions for many years to come.

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