Articles

Working Memory

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The term working memory refers to a brain system that provides temporary storage and manipulation of the information necessary for such complex cognitive tasks as language comprehension, learning, and reasoning. This definition has evolved from the concept of a unitary short-term memory system. Working memory has been found to require the simultaneous storage and processing of information. It can be divided into the following three subcomponents: (i) the central executive, which is assumed to be an attentional-controlling system, is important in skills such as chess playing and is particularly susceptible to the effects of Alzheimer's disease; and two slave systems, namely (ii) the visuospatial sketch pad, which manipulates visual images and (iii) the phonological loop, which stores and rehearses speech-based information and is necessary for the acquisition of both native and second-language vocabulary.

The question of whether memory should be regarded as a single unitary system or whether it should be fractionated into two or more subsystems formed one of the major controversies within cognitive psychology during the mid-1960s. During that time, evidence began to accumulate in favor of a dichotomy (*1*). Some of the most convincing evidence came from the study of brain-damaged patients; those suffering from the classic amnesic syndrome appeared to have gross disruption of the capacity to form new lasting memories but showed preserved performance on a range of tasks that were assumed to test short-term memory (*2*). Conversely, a second type of patient was identified who appeared to show normal long-term learning but had a short-term memory span limited to one or two items (*3*). It was suggested that such patients had a deficit in short-term storage, in contrast to the long-term storage deficit that occurs in the amnesic syndrome. This finding, together with considerable evidence from the study of normal subjects, appeared by the late 1960s to argue for a dichotomous view of memory, such as that proposed by Atkinson and Shiffrin (*4*).

By the early 1970s it was becoming clear that the two-component model was running into difficulties. One of its problems was inherent in the neuropsychological evidence that initially appeared to support it so strongly. Atkinson and Shiffrin (*4*) suggested that the short-term store within their model acted as a working memory, being necessary for learning, for the retrieval of old material, and for the performance of many other cognitive tasks. If that were the case, one would expect patients with a grossly defective short-term store to show many other cognitive problems, including impaired long-term learning. In fact, such patients appeared to have a normal long-term learning capacity and surprisingly few cognitive handicaps.

Pursuing this issue was difficult because patients with a pure short-term memory deficit are rare. We therefore attempted to simulate this condition in unimpaired subjects by using a dual-task technique (*5*). We argued as follows: if the digit-span procedure depends on the short-term store, with the number of digits retained determined by the capacity of the store, then it should be possible to interfere systematically with the operation of the working memory system by requiring the subject to remember digits while performing other cognitive tasks. As the concurrent digit load is increased, the remaining short-term capacity would decrease and the interference would increase, with performance presumably breaking down as the digit load reached the capacity of the system.

Reasoning, comprehension, and learning tasks all showed a similar pattern. As concurrent digit load increased, performance declined, but the degree of disruption fell far short of that predicted. Subjects whose digit memory was at full capacity could reason and learn quite effectively.

These results, together with others, encouraged the abandonment of the idea of a single unitary short-term store that also functions as a working memory. Instead, we proposed the tripartite system shown in Fig. 1, which comprises an attentional controller and the central executive, supplemented by two subsidiary slave systems. The articulatory or phonological loop was assumed to be responsible for maintaining speech-based information, including digits in the digit span test, whereas the visuospatial sketch pad was assumed to perform a similar function in setting up and manipulating visuospatial imagery.

The concept of working memory has increasingly replaced the older concept of short-term memory (*6*). Research has subsequently tended to concentrate on one of two complementary but somewhat different approaches. One of these defines working memory as the system that is necessary for the concurrent storage and manipulation of information; tasks are devised that combine processing and storage, and the capacity of such tasks to predict a range of other cognitive skills, such as reading, comprehension, and reasoning, is tested. This psychometric approach, which has flourished most strongly in North America, frequently focuses on the extent to which performance on working memory tasks can predict individual differences in the relevant cognitive skills.

An alternative approach, which has been more favored in Europe, uses both dual-task methodology and the study of neuropsychological cases in an attempt to analyze the structure of the working memory system. Most effort has been devoted to the two slave systems, on the grounds that these offer more tractable problems than the more complex central-executive system.

The two approaches are complementary, and both have strengths and weaknesses; the psychometric correlational approach has the advantage that it can tackle what is probably the most crucial component of the system, the central executive, and can furthermore work directly on problems of practical significance, such as reading

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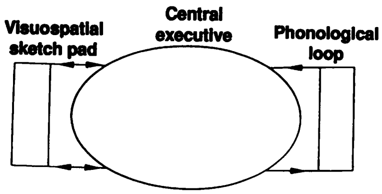

Fig. 1. A simplified representation of the Baddeley and Hitch working memory model (*5*).

comprehension or the reasoning tasks used in tests of intelligence. The weakness of this approach lies in the reliance on complex working memory tasks that have a somewhat arbitrary construction and that do not readily lend themselves to a more detailed analysis of the component processes. The dual-task and neuropsychological approach can be utilized to successfully analyze the constituent processes of the slave systems but has made less headway in teasing apart the complexities of the executive controller.

Individual Differences in Working Memory

The essence of the psychometric approach is to develop tasks that require the combined storage and manipulation of information and to correlate performance on these tasks with the performance of practically and theoretically important cognitive skills. One influential study in this area was carried out by Daneman and Carpenter (*7*), who examined the processes involved in reading comprehension. They devised a series of working memory tasks, one of which required subjects to read aloud or listen to a series of short sentences while retaining the last word from each sentence for subsequent immediate recall. Hence, subjects might read or hear: "The sailor sold the parrot. The vicar opened the book." They should then respond "parrot, book." The test typically starts with two sentences and increases to a point at which subjects are no longer able to recall all the terminal words. This point is designated the subject's working memory span.

Daneman and Carpenter, and others using similar techniques, typically found a correlation coefficient of about 0.5 or 0.6 between working memory span and reading comprehension, as measured by standardized tests (*8*). The span task does not have to involve language processing because similar correlations are found when simple arithmetic, combined with word recall, is substituted for sentence processing (*9*).

Subsequent studies have indicated that students with high working memory span were better at coping with "garden path sentences," which contain misleading context, and that they are better at drawing inferences from text, suggesting that they have a better grasp of its meaning (*10*).

A second area in which the individual differences approach has been applied to the analysis of working memory is concerned with the study of reasoning and concentrates particularly on tasks that have traditionally been used to measure intelligence. One example of this is the working memory analysis by Carpenter, Just, and Shell (*11*) of performance on the Raven's matrices task, a test in which one sector is missing from a complex pattern and the subject is required to choose which of six possible options offers the best completion. Christal (*12*) has also shown that working memory tests provide improved prediction of technical learning capacity in U.S. Air Force recruits, when compared with more scholastic measures.

Kyllonen and Christal (*13*) have carried out a series of studies, each involving several hundred subjects who were required to perform a number of standardized tests of reasoning of the type used to assess intelligence as well as a range of tasks that had been devised to estimate working memory capacity. For each study, their results suggested a very high correlation between working memory capacity and reasoning skill. They concluded, however, that the two concepts, although closely related, were not synonymous; reasoning performance was more dependent on previous knowledge than was working memory, which in contrast appeared to be more dependent on sheer speed of processing.

Components of Working Memory

Although concurrent storage and processing may be one aspect of working memory, it is almost certainly not the only feature; indeed, Baddeley, Barnard, and Schneider and Detweiler (*14*) all suggest that the coordination of resources is the prime function of working memory, with memory storage being only one of many potential demands that are likely to be made on the system.

One proposed role for the central executive is that of coordinating information from two or more slave systems. This feature of the central executive was used in an attempt to test the proposal that Alzheimer's disease is associated with a particularly marked deficit in central executive functioning (*15*). Patients with Alzheimer's disease, and both young and elderly normal subjects, were required to perform two tasks concurrently, one visual and one verbal. The difficulty of each task was adjusted so that the Alzheimer patients were making the same proportion of errors as the control subjects, and subjects were then required to perform both tasks at the same time. Normal elderly subjects were no more impaired than young controls by this requirement to coordinate, whereas the Alzheimer patients showed a marked impairment in performance on both the memory and tracking tasks when required to combine them (*16*). As the disease progressed, performance on the individual tracking and memory span tasks held up very well (Fig. 2), whereas performance on the combined tasks deteriorated markedly, as would be predicted by the hypothesis of a central executive deficit in Alzheimer's disease (*17*).

The Slave Systems of Working Memory

Although an analytic approach to the central executive is beginning to bear fruit, there is no doubt that considerably more progress has been made with the simpler task of understanding the peripheral slave systems of working memory. The dual-task paradigm has been used to demonstrate the separability of the memory systems responsible for learning by means of visuospatial imagery and of learning by rote repetition. Imagery is disrupted by the requirement of performing a visuospatial task, such as tracking a spot of light moving on a screen, by certain types of eye movement, or by the presentation of irrelevant visual material during learning (*18*).

There are separable spatial and visual components, with different

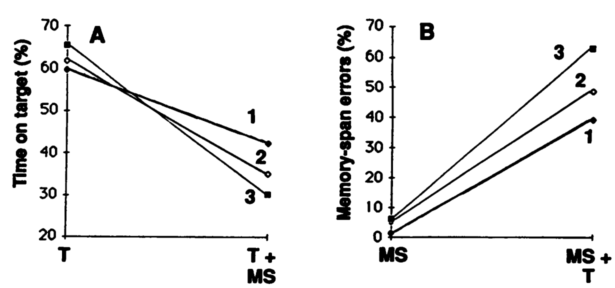

Fig. 2. Dual-task performance of patients with Alzheimer's disease in a series of three sequential tests (1, 2, and 3) 6 months apart. T, tracking task; MS, memory span task. Normal subjects did not show a difference between single and dual-task conditions. Data from Baddeley *et al.* (*17*).

tasks differentially recruiting the two. Farah (*19*) distinguishes one imagery component that is principally concerned with the representation of pattern information and that involves the occipital lobes from a second more spatial component that seems to be dependent on parietal lobe functioning. Neuropsychological evidence supports this dichotomy, with some patients having great difficulty in imaging and recalling such visual features as the shape of the ears of a spaniel dog or the color of a pumpkin but having no difficulty in spatial tasks such as describing routes or locating towns on maps; other patients show exactly the reverse pattern of deficits (*20*).

Having found ways of separately disrupting spatial and verbal processing, one can explore the relative contribution of different subsystems to complex tasks. One example of this application concerns the nature of the cognitive processes involved in playing chess. The literature reviewed by Holding [in (*21*)] indicates that both visual and verbal coding have been claimed to be crucial by different studies that principally rely on subjective report. We have sought more objective evidence through a series of experiments that utilize the secondary-task technique to disrupt either the phonological loop, the sketch pad system, or the central executive. Our first study involved memory for complex chess positions and tested subjects ranging from the modest club player to the international grand master. As expected, expertise correlated highly with memory performance, but all subjects showed the same basic pattern: no disruption from the concurrent verbal task but clear impairment from the tasks occupying the visuospatial sketch pad or the central executive. A second study required subjects to choose the optimum next move from a complex middle-game position and found exactly the same pattern. Disruption of verbal activity had no effect, whereas visuospatial disruption was clear, and this problem-solving task was even more susceptible to central executive disruption than the task in the first study (*22*).

Analyzing the Phonological Loop

The phonological loop is probably the simplest and most extensively investigated component of working memory. It lies closest to the earlier concept of short-term memory and has been investigated most extensively with the memory-span procedure. It is assumed to comprise two components, a phonological store that can hold acoustic or speech-based information for 1 to 2 seconds, coupled with an articulatory control process, somewhat analogous to inner speech. This system serves two functions; it can maintain material within the phonological store by subvocal repetition, and it can take visually presented material such as words or nameable pictures and register them in the phonological store by subvocalization.

This simple model is able to give a good account of a rich range of laboratory-based findings. These include the following:

1) *The acoustic similarity effect.* This is the observation that the immediate ordered recall of items is poorer when they are similar rather than dissimilar in sound (*23*). Hence, hearing and repeating dissimilar words such as "pit, day, cow, pen, rig," is easier than a phonologically similar sequence such as "man, cap, can, map, mad." This phenomenon is assumed to occur because the basic code involved in the store is phonological; similar items have fewer distinguishing cues than dissimilar items and are therefore more susceptible to being forgotten. Similarity of meaning does not have this effect, suggesting that this subsystem does not reflect semantic coding.

2) *The irrelevant speech effect.* This refers to a reduction in recall of lists of visually presented items brought about by the presence of irrelevant spoken material (*24*). Once again, the semantic characteristics of the material are not important, with a language that is unfamiliar to the subject being just as disruptive as words in his or her native tongue and nonsense syllables being as disruptive as meaningful words. The effect is not due to simple distraction, because loud bursts of noise have little or no effect (*25*). These results are interpreted under the assumption that disruptive spoken material gains obligatory access to the phonological memory store.

3) *The word-length effect.* This provides evidence on the nature of the subvocal rehearsal process. Memory span for words is inversely related to spoken duration of the words. Subjects can generally remember about as many words as they can say in 2 seconds (*26*). This phenomenon accounts for differences in digit span when subjects are tested in different languages; languages in which digits tend to have long vowel sounds or more than one syllable take longer to rehearse and lead to shorter memory spans (*27*). The model can also explain the marked tendency for digit span in children to increase with age; as children get older, they are able to rehearse faster (*28*).

4) *Articulatory suppression.* It is possible to disrupt the use of subvocal rehearsal by requiring subjects to utter some repeated irrelevant sound, such as the word "the." This process, known as articulatory suppression prevents the subjects from rehearsing the material they are trying to remember and thus removes the effect of word length. Suppression also prevents subjects from registering visually presented material in the phonological store. Recall of such visual material is reduced, and the acoustic similarity effect is abolished (*29*).

The performance of neuropsychological patients with impaired short-term memory can also be explained as a deficit in the phonological store. They typically show no evidence of phonological coding in memory tasks when presentation is visual, no word length effect, and no influence of articulatory suppression, suggesting that these patients make little or no use of their defective phonological short-term store (*30*).

The Function of the Phonological Loop

Patients with a specific phonological loop deficit seem to have remarkably few signs of general cognitive impairment. Although they typically have difficulty in comprehending certain types of complex sentences, interpretation of results in this area remains controversial (*31*). The most commonly held view is that the phonological store serves as a backup system for comprehension of speech under taxing conditions but may be less important with simple, clearly presented material.

In recent years we have been exploring another possible function of this system, namely, its role in long-term phonological learning, such as acquiring the vocabulary of one's native, or even a foreign, language. In one study, we asked a patient with a very specific short-term phonological memory deficit to learn eight items of Russian vocabulary, a language with which the patient was unfamiliar; we compared the results with the patient's capacity to learn to associate arbitrary pairs of words in the patient's native language (*32*). People tend to learn pairs of familiar words in terms of their meaning, and, as expected, the patient's performance on this task was entirely normal. In contrast, the patient failed to learn the Russian words with auditory presentation and was severely impaired relative to control subjects even when presentation was visual. This result suggests that short-term phonological storage is important for new long-term phonological learning. Subsequent studies with normal adults have shown that factors that influence the phonological loop, such as articulatory suppression, word length, and phonological similarity, strongly influence foreign vocabulary acquisition yet show no effect on learning to associate pairs of familiar words (*33*).

Evidence for the importance of the phonological loop in native-language learning comes from a number of sources. Gathercole and Baddeley (*34*) studied a group of children with a specific language disorder and found that their most striking cognitive deficits occurred in a task involving hearing and repeating back unfamiliar nonwords; on this nonword repetition task, 8-year-old children with the language development of 6-year-olds functioned like 4-year-olds. Further investigation suggested that this was due neither to perceptual difficulties nor to difficulties in speech production but probably resided in the operation of the phonological short-term store.

A subsequent study assessed the role of the phonological short-term store in the development of vocabulary across the normal range (*35*). A sample of 118 children was tested after starting school between the ages of 4 and 5 years. Their capacity for nonword repetition was measured, as was their nonverbal intelligence and their vocabulary, which was tested by speaking a series of words to the children and requiring them to point to appropriate pictures. Nonword repetition proved to be highly correlated with vocabulary and to be a powerful predictor of vocabulary 1 year later.

In an experimental simulation of new word learning (*36*), we taught children new names for toy monsters. Two groups were tested that were matched for nonverbal intelligence but that differed in nonword repetition capacity. Those with low capacity showed poor learning, particularly in the case of unfamiliar invented names.

Service (*37*) has studied the acquisition of English as a second language by young Finnish children. Service took a number of measures of cognitive skill before the course began, including measures of nonverbal intelligence and of nonword repetition capacity. Two years later the children's performances on a range of tests of English language were correlated with these earlier measures. Once again, nonword repetition capacity, which is assumed to depend on short-term phonological storage, was clearly the best predictor of subsequent success. Thus, the evidence supports the view that short-term phonological memory is crucial in the acquisition of vocabulary.

Conclusion

The concept of a working memory system that temporarily stores information as part of the performance of complex cognitive tasks is proving to be productive. Studies that have utilized the individual difference approach have linked working memory to performance on a range of important tasks, including language comprehension and reasoning. The more analytic approach has shown that the concept forms a useful conceptual tool in understanding a range of neuropsychological deficits, which in turn have thrown light on normal cognitive functioning.

Working memory stands at the crossroads between memory, attention, and perception. In the case of the slave systems, the phonological loop, for example, probably represents an evolution of the basic speech perception and production systems to the point at which they can be used for active memory. Any adequate model of the phonological loop is thus likely to overlap substantially with an adequate model of speech perception and speech production. The visuospatial sketch pad is probably intimately related to the processes of visual perception and action. The central executive clearly reflects a system concerned with the attentional control of behavior, with subsequent developments almost certainly depending on parallel developments in the study of attention and of the control of action. If these links can be sustained and developed, the concept of working memory is likely to continue to be a fruitful one.

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