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Anthony A. Wright

HUMANS

Working memory is a system that provides short-term storage of information used in complex cognitive activities such as planning, reasoning, problem-solving, and language. This mental blackboard is a temporary workspace that makes possible the examination, manipulation, and tranformation of internally represented information during these cognitive activities—and also allows its subsequent erasure.

Suppose you ordered three bottles of mineral water at $1.80 a bottle and gave the waiter ten dollars. How much change would you expect? Working this out would likely involve retaining the results of your initial calculations while performing other operations, storing interim results for which you would have no need after arriving at the answer and the details of which would likely escape you upon subsequent inquiry. The temporary storage and manipulation of information required to perform this and many similar tasks is working memory.

Short-Term versus Working Memory

Researchers have long accepted this idea of a form of separate, temporary memory storage—one quite distinct from the system of long-term storage—for many years. In the nineteenth century William James (1890) proposed the term *primary memory* for a form of temporary storage that was at least partly responsible for the experience of what he termed "the specious present," the experience that time is continuous, extending beyond the consciousness of the currently encountered microsecond.

Despite the theorizing of James, the twentieth century saw little interest in the mental capacity for short-term storage until the 1950s, which saw the rise of a "cognitive revolution," a surge of interest in the information-processing approach to the analysis of human cognition that used the newly developed digital computer as a basis for new theories of the workings of the mind. This sea change, coupled with some of the practical problems that had arisen from the attempt to apply psychology to wartime issues, led to renewed interest in both attention and short-term storage, thanks in good measure to the work of Broadbent (1958).

By the late 1960s a general consensus emerged in favor of the separation of memory into at least two systems: a short-term, limited-capacity store that can hold information for a matter of seconds and that feeds a far more capacious and durable long-term store. The dominant model of this period was that proposed by Atkinson and Shiffrin, in which information passes through a series of brief sensory registers that are part of the processes of perception and then moves into a limited-capacity short-term store. The latter acts as a working memory, with a series of strategies or controls that organize and maintain incoming material to optimize learning and subsequent recall. This model gives a good account of the available data and is still portrayed as the dominant view of memory in many introductory textbooks.

Nevertheless, despite its attractive simplicity, the model soon began to encounter problems. One difficulty was its learning assumption: the longer an item is held in short-term storage (STS), the greater is its probability of transfer into long-term memory. Evidence conflicting with this assumption came from data that initially seemed to support the two-store model. Patients suffering from amnesia following brain damage appeared to show drastic impairment of long-term learning but retained their short-term store (Baddeley and Warrington, 1970). Conversely, Shallice and Warrington (1970) identified other patients showing exactly the opposite pattern: normal long-term learning but problems on short-term memory tasks. The double dissociation found in such patients conformed to the Atkinson and Shiffrin model quite nicely, except for one crucial point: If, as the model proposed, short-term storage was a crucial working memory that made learning and long-term storage possible, then how could patients with a gross disruption of the short-term store learn and recall normally? A defective short-term store should have led to massive problems in learning, memory, and general cognition if this system indeed served as a working memory.

The Baddeley and Hitch Model

Baddeley and Hitch (1974) tried to clarify the problems in the Atkinson and Shiffrin model by attempting to simulate in normal subjects the deficits suffered by patients with short-term memory problems. They attempted to disrupt short-term memory function by requiring the subject to perform a memory-span task while attempting to learn, reason, or comprehend. The two-store model should predict that requiring the subject to maintain a string of, say, six digits would nearly fill the limited-capacity short-term store. If the latter acts as a crucial working memory, then the subject's capacity for other tasks should be almost totally disrupted. The pattern of results obtained across a range of activities was quite consistent. While there was indeed some impairment, even a concurrent load of six numbers produced only modest disruption, even in the capacity to perform quite demanding reasoning tasks. Baddeley and Hitch (1974) concluded that these results were inconsistent with the Atkinson and Shiffrin model (1968), and proposed an alternative multicomponent model to replace the unitary short-term store.

The Baddeley and Hitch working memory model consisted of three components: an attentional control system they termed the central executive and two subsidiary slave systems, the phonological loop which maintains and manipulates speech-based information, and the visuospatial sketchpad which provides a temporary storage system for visuospatial information (see Figure 1). This model still remains as the most widely accepted account of the function and organization of working memory, and as such merits further description.

Figure 1

SOURCE: Courtesy of Todd S. Braver.

The structure of working memory proposed by Baddeley and Hitch. The boxes labeled phonological loop, central executive, and visuospatial scratchpad represent the proposed components or subsystems of working memory.

The phonological-loop component seems to be made up of two subcomponents, a store that will hold auditory-verbal memory traces for about two seconds and a subvocal rehearsal process. This process can both maintain the items within the store by recycling them subvocally and register visually presented items in the store by means of subvocalization. The short-term phonological storage system seems specially adapted to language learning since it provides critical mechanisms for keeping novel phonological strings active and in the correct serial order that allows their binding to appropriate meanings. Evidence supporting this hypothesis comes from studies of vocabulary acquisition in children, in whom the functioning of the phonological store predicts individual differences in language-learning skills (Baddeley, Gathercole, and Papagno, 1998).

The visuospatial sketchpad may represent a separate system specializes in the maintenance of information using visuospatial rather than linguistic codes (i.e., mental images). There is evidence that it may constitute two subsystems, one concerned with spatial information and the relative location of objects and the with pattern information. Patients with a disruption to the operation of the spatial system may have difficulty in finding their way around but have no problem in recalling or using information concerning the visual characteristics of objects, such as the color of a banana or the shape of a dachshund's ears. Other patients show the opposite pattern of deficits (Farah, 1988). Some research suggests that rehearsal of information in the sketch pad might be similar to shifting spatial attention, and as such appears to be linked to the brain system that controls eye movements (Awh and Jonides, 2001).

The central executive, the most complex and least understood component of working memory, at first seemed to operate along the lines of the model of attentional control proposed by Norman and Shallice (1986). This model assumes that continual activity is controlled in two major ways: by the running off of existing programs or scripts, or by the intervention of the supervisory attentional system (SAS). The latter is capable of interrupting continual semiautomatic programs when they reach an impasse or when longer-term goals demand a departure from the continual activity. A secondary function proposed for the central executive was to coordinate and integrate the operation of the two buffer systems in tasks requiring either simultaneous or alternating storage of both verbal and visuospatial information.

The influential Baddeley and Hitch model spawned a great deal of research in the 1970s and 1980s, much of it geared toward the study of the properties of the two slave storage systems, especially that of the phonological loop. A second theme of research on working memory during this period was an examination of its role in individual differences in higher-level cognitive abilities. In 1980, Daneman and Carpenter suggested that verbal working memory capacity could predict abilities in a range of general language skills, such as reading comprehension and verbal SAT scores (Daneman and Carpenter, 1980). Verbal working memory capacity was measured using a task called the reading span, which determines how many words the subject can retain in short-term memory while simultaneously performing intervening language-processing tasks (reading sentences out loud). Subsequent studies have validated and replicated the original findings using a variety of similar span tasks and cognitive predictors. Many theorists now believe that working-memory capacity might serve as a strong analogue to the notion of a domain-general intelligence factor (Engle, Tuholski, Laughlin, and Conway, 1999). Other studies have supported the notion of the Baddeley and Hitch model that there are two separate working-memory capacities, with one predicting verbal abilities and the other predicting visuospatial ones (Shah and Miyake, 1996).

Mechanisms of Working Memory

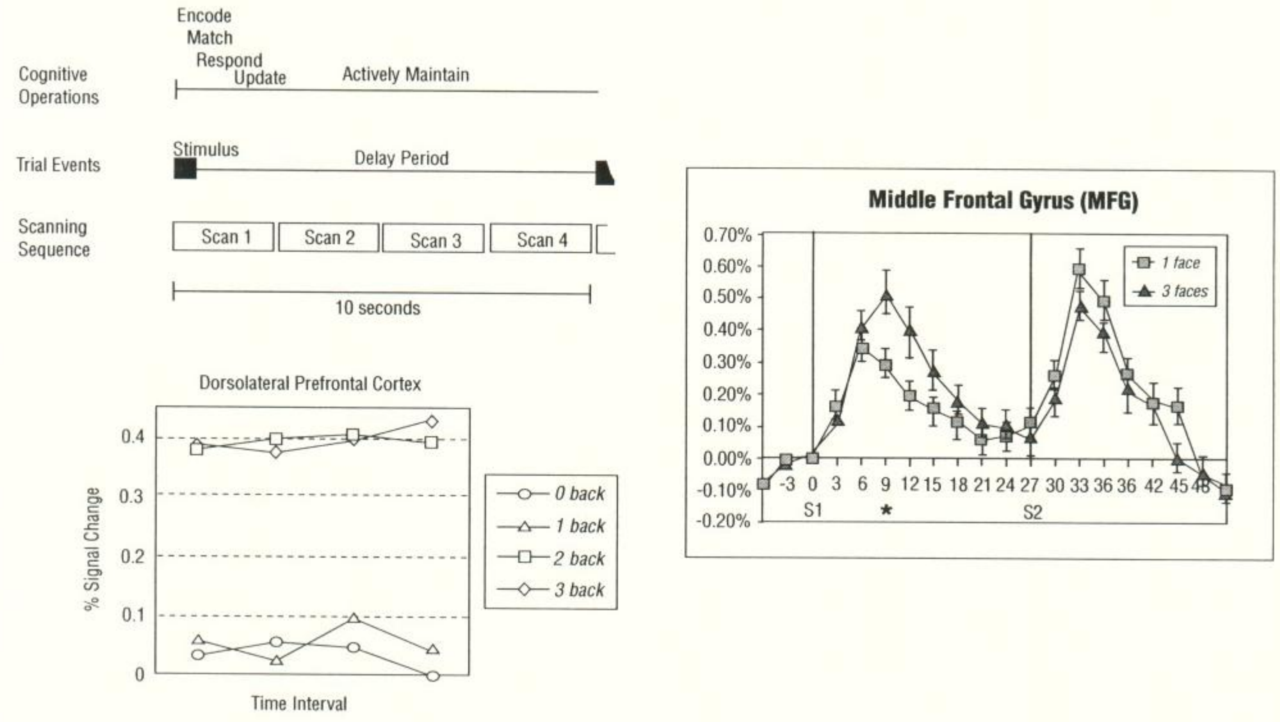
Since 1990, the focus of research on working memory has shifted to a more thorough study of its critical psychological and biological mechanisms: How do the components of working memory "work" and how does the brain implement them? This trend has been driven by the rise of cognitive neuroscience as a discipline and also by the development of new experimental methods such as human brain imaging for studying working memory. For example, nonhuman primate research has suggested that active maintenance of information through the sustained firing of neuronal populations provides a cellular mechanism of working memory (Goldman-Rakic, 1995). This short-term storage mechanism contrasts sharply with the cellular mechanisms that seem to underlie long-term memory—the strengthening of (synaptic) connections between neurons.

A primary focus of both the animal and human brain imaging studies of working memory has been the prefrontal cortex. For example, when humans perform working memory tasks, there is a reliable sustained increase in activity within the prefrontal cortex during maintenance periods, with the magnitude of increase related to working memory load. This finding has been demonstrated using a number of simple task paradigms, including the N-back (Cohen et al., 1997) and Sternberg item-recognition task (Jha and McCarthy, 2000). Both tasks are delayed-response paradigms in which the information to be stored in working memory must be matched against a subsequent probe item, changes from trial to trial, and can vary in the number of items that must be held and in the delay period of maintenance. In the N-back a continuous sequence of items is presented one at a time, each requiring a determination whether it matches an item presented a specified number (N) of trials back (e.g., in a three-back condition the last A in the sequence ABCA would be considered a match). Thus, the task requires that a previous item must be maintained in its appropriate sequence and stored over intervening items. The Sternberg task is similar but typically presents the memory set simultaneously followed by an unfilled delay interval. Figure 2 shows data on the time course of prefrontal cortex activity as a function of working-memory load in both the N-back and Sternberg tasks.

Other brain-imaging research on working memory has provided converging support for the Baddeley and Hitch model by suggesting that there is a neuroanatomical segregation of verbal and visuospatial short-term storage, of storage and rehearsal in verbal working memory, and of maintenance and manipulation (e.g., central executive) functions (Smith and Jonides, 1999). These findings remain controversial because not all studies have observed such distinctions. One possibility is that the components of the model do not cleanly map on to the brain, especially as regards the relationship between the maintenance and control functions of working memory.

As a consequence, attention has turned toward gaining a better understanding the nature of the executive-control functions needed for successful working memory during complex cognition. A first critical question is whether separable control functions play different roles within working memory. A number of possible control operations have been suggested, such as the following: shifting or switching attention between the mental sets needed to perform different tasks; inhibition or suppression of inappropriate response tendencies or irrelevant information; moni-

Figure 2



SOURCE: Courtesy of Todd S. Braver.

(Left) Activation of prefrontal cortex (dorsolateral region) during performance of the N-back task. The upper panel refers to the experimental design of the study, in which four brain imaging scans were acquired during the course of each trial. Because of the long delay interval (10 seconds) between trials, activity reflecting active maintenance should be present during the later scans of each trial (scans 3 and 4). The lower panel shows the average activity level in this prefrontal cortex region across four different N-back conditions (0-back through 3-back) during the course of a trial. The greater activity for 2-back and 3-back conditions relative to 0-back and 1-back conditions reflects sensitivity to working memory load. The constant level of activity across the trial suggests a sustained response reflecting active maintenance. Adapted from Cohen, J. D., Perstein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J., and Smith, E. E. (1997). Temporal dynamics of brain activation during a working memory task. *Nature 386,* 604–608. (Right) Activation of prefrontal cortex (same dorsolateral region) during performance of Sternberg task using faces as stimulus items. Activation is plotted from the time of the presentation of the memory set (S1) to the time of the subsequent probe item (S2), which occurred 27 seconds later. The increased activation for the 3-face condition reflects a sensitivity to working memory load. The increased activity (relative to the pretrial baseline) throughout the delay interval suggests that the response reflects active maintenance. Adapted from Jha, A. P., and McCarthy, G. (2000). The influence of memory load on delay-interval in a working-memory task: An event-related functional MRI study. *Journal of Cognitive Neuroscience 12,* 90–105.

toring and updating the contents of working memory; temporal tagging or contextual coding of incoming information; and planning or sequencing intended actions (Smith and Jonides, 1999). Some evidence suggests the statistical independence of these functions (Miyake et al., 2000); but it is unclear whether these functions are instantiated by truly separable systems or might be further reducible to a more fundamental, unitary set of mechanisms.

A second central issue is the exact relationship between the mechanisms supporting active maintenance and those that control this process. Models such as that of Baddeley and Hitch suggest a strict segregation between maintenance and control functions. Yet other models suggest that these functions are more tightly intertwined, with active maintenance of goal representations serving as a primary means of control (O'Reilly, Braver, and Cohen, 1999). One view argues for a distinction between two types of maintenance mechanisms: goal-related information maintained in the focus of attention that is robustly protected from interference and transiently activated (via spreading associative processes) information from long-term memory that decays over brief intervals (Cowan, 1995). The first mechanism seems more domain-general and may reflect the functions of the prefrontal cortex; the second mechanism likely reflects more domain-specific maintenance operations that are widely distributed across different brain regions. However, the two sources of working memory seem to be interdependent, with actively maintained goal information biasing the time course of activated long-term memory (through refreshment or suppression). Conversely, spreading activation of long-term memory elements might drive the activation or updating of goal representations.

Many studies have suggested that the individual differences in working-memory capacity most strongly related to skill in complex cognitive tasks (and constructs of fluid intelligence) are those pertaining to goal-maintenance mechanisms rather than to the activation of long-term memory elements (Kane, Bleckley, Conway, and Engle, 2001). Thus, the notion of working-memory capacity may be a misnomer, referring not to the number of items that can be maintained simultaneously but rather to the efficacy with which an individual can represent and maintain even a single goal within the focus of attention in the face of interference and distraction.

There is much still to be understood about the nature and mechanisms of working memory. Progress in understanding working memory will likely come from the further specification of mechanisms that arise both from direct comparisons between models and from their implementation in explicit computational formalisms (Miyake and Shah, 1999). Nevertheless, the general concept of a working memory system that provides temporary storage for a wide range of cognitive activities has proved to be a useful one, and is likely to remain so. While theoretical models of working memory are likely to change and become more complex, the study of working memory is likely to significantly inform such diverse cognitive domains as attention, reasoning, language, individual difference, and the executive control of behavior.

See also: JAMES, WILLIAM; LONG-TERM POTENTIATION; PREFRONTAL CORTEX AND MEMORY IN PRIMATES; SENSORY MEMORY

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