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Colloquium Paper

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The fractionation of working memory

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ABSTRACT In performing many complex tasks, it is necessary to hold information in temporary storage to complete the task. The system used for this is referred to as working memory. Evidence for the need to postulate separable memory systems is summarized, and one particular model of working memory is described, together with its fractionation into three principal subsystems. The model has proved durable and useful and, with the development of electrophysiological and positive emission tomography scanning measures, is proving to map readily onto recent neuroanatomical developments.

Within cognitive psychology, the concept of working memory represents a modification and extension of an earlier concept, short-term memory, a limited-capacity temporary memory store, typified by the model proposed by Atkinson and Shiffrin (1). The concept of working memory differs from that of short-term memory in two respects: (*i*) it is assumed to involve a number of subsystems, rather than a unitary module; and (*ii*) there is considerable emphasis on its functional role in other cognitive tasks such as learning, reasoning, and comprehension.

Unfortunately, the situation is further complicated by the fact that the term working memory was adopted independently in two other research areas. One use of the term stemmed initially from a learning paradigm in which rats were placed in a radial arm maze, where they had to retrieve food from each arm, remembering not to return to that arm again, since it would now be devoid of food and would remain so until the next test session, typically on another day (2). While this bears some similarity to the term working memory in humans, in fact, performance on this task in human subjects is likely to depend on long-term memory rather than working memory.

A second use of the term comes from the computational modeling approach developed by Newell and Simon (3), in which the term working memory is used to refer to the component that holds what they term production systems, an important part of the model. They make it clear, however, that the working memory component of their model does not map in any simple or direct way onto an equivalent component of human memory.

Within human experimental psychology, however, and for present purposes, the term working memory is taken to apply to a limited capacity system that is capable of storing and manipulating information and that is assumed to be an integral part of the human memory system. This interpretation of the concept that has proved widely applicable to a broad range of subject and patient groups (4) and will be described below.

How Many Kinds of Memory?

Although Hebb (5) speculated on the possible existence of two kinds of memory, long-term and short-term, his proposal was largely ignored until the demonstration in the late 1950s by Brown (6) in England and the Petersons (7) in Indiana that even a small amount of material, such as three consonants, would be forgotten within seconds unless the subject was allowed to maintain them by active rehearsal. Both studies postulated the existence of a temporary short-term memory system within which memory traces spontaneously faded within seconds, proposing that the system was limited in storage capacity and contrasting it with long-term memory, which had massive capacity and durability. This challenge to contemporary orthodoxy was resisted (8), leading to a period of intense experimental activity in the 1960s. On balance, the evidence seemed to support a dual system: many separate models were proposed, but most influential was that of Atkinson and Shiffrin (1). This model proposed that information from the environment passes through a series of brief sensory memories that are essentially part of the process of perception before reaching a short-term or working memory. This forms a limited capacity bottleneck that is necessary both for registering new information in long-term memory and for its manipulation and retrieval.

Evidence for this view came from many sources, of which three were particularly influential, namely: (*i*) two-component tasks, (*ii*) differential coding, and (*iii*) neuropsychological evidence.

Two-Component Tasks. A number of tasks appear to reflect two quite separate memory processes, which were assumed to relate to long- and short-term memory, respectively. The most characteristic of these is the task known as free recall, in which the subject is presented with a list of unrelated words and invited to recall as many as possible in any order, immediately after presentation. Under these circumstances, the last few items presented tend to be particularly well-recalled, a phenomenon known as the recency effect. If, however, recall is delayed for 5–10 sec, during which the subject is prevented from rehearsing, then the recency effect disappears while the delay has little or no effect on the recall of earlier items, suggesting that the recency items may have been held in a temporary store while earlier items are held in a more durable long-term store (9).

Differential Coding. The second popular technique used to study short-term or working memory is that of immediate serial recall or memory span, in which a subject is presented with a string of items, such as the digits comprising a telephone number, and required to recall them in the appropriate order. As sequence length increases, the probability of correct recall declines, the maximum length the subject can recall being referred to as the memory span. Conrad (10) observed that when subjects were recalling sequences of consonants, their errors tended to be similar in sound to the correct item (for example, b being recalled as v), even though presentation was visual.

Further evidence for some form of acoustic or phonological code comes from the observation that recall of sequences of items that sound similar is more prone to error than recall of dissimilar sequences. Hence, subjects asked to recall the

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sequence man, cat, map, can, mat recalled the sequence correctly on only ≈20% of occasions, compared with ≈80% recall of a dissimilar sequence such as pet, day, cow, pen, sup. The similarity of meaning involved in a sequence such as big, huge, large, wide, tall, on the other hand, had little or no effect on performance (11). When the paradigm was changed by lengthening the sequence to 10 items and testing was performed by delayed recall so as to demand the utilization of long-term memory, then the pattern changed, with similarity of meaning becoming crucial and acoustic similarity losing its influence (12). Under these conditions, therefore, it appears that short-term memory adopts an acoustic code, whereas long-term memory operates most effectively when registering the novel material in terms of meaning.

Neuropsychological Evidence. It had been known for some time that densely amnesic patients who appear to be incapable of registering new information in long-term memory may nonetheless have normal memory span (13, 14), suggesting that they may have preserved short-term memory. Further evidence for this was presented by Baddeley and Warrington (15), who also demonstrated that amnesic patients show a normal recency effect in free recall and may perform normally on the Peterson and Peterson short-term forgetting task, provided that they are intellectually unimpaired apart from their amnesia. Shallice and Warrington (16) demonstrated the converse pattern in a group of patients who typically had damage to the perisylvian region of the left hemisphere. Such patients perform very poorly on verbal memory span tasks and show virtually no recency, but nonetheless appear to have well preserved long-term memory capacity. This pattern of results argues strongly for the separation of long- and short-term memory systems.

At first sight the weight of evidence seemed to argue strongly in favor of a system such as that proposed by Atkinson and Shiffrin (1), with a temporary short-term system that controls input into and out of long-term memory. More detailed consideration, however, suggests a major problem. If short-term memory forms a crucial link in the chain of learning and cognition, then patients with a deficit in this system should have problems in long-term learning and retrieval, not to mention the many other tasks such as comprehension and reasoning that were assumed to depend upon the short-term working memory system. However, not only were such patients able to perform well on long-term memory tasks, they also seemed to have remarkably few problems in their everyday life. One such patient was a very efficient secretary, while a second ran a shop and looked after a family. Furthermore, the assumptions concerning the process whereby information was transferred from short- to long-term memory within the Atkinson and Shiffrin model was heavily criticized (e.g., ref. 17), and, by the early 1970s, interest in short-term memory began to wane.

Working Memory

In an attempt to tackle this paradox, Baddeley and Hitch (18) developed a procedure whereby the hypothetical short-term memory system was systematically manipulated by requiring the subject continuously to rehearse a sequence of digits while performing a task such as reasoning that was assumed to depend on short-term memory. The digit load ranged from one item to eight, slightly beyond the immediate memory span of most subjects. It was assumed that the longer the sequence, the more of the capacity of the memory system would be occupied, leaving progressively less capacity for performing other tasks, such as reasoning, comprehending, and learning, which should thus show a progressive decline in performance. The results were somewhat unexpected. Although speed of performance declined with increasing load, accuracy remained high. Furthermore, the decrement in speed was far from catastrophic, even at maximum load, suggesting some overlap of function between the system responsible for holding digits and the general short-term memory system, but implying that the two were far from identical.

In response to this and a range of similar results, Baddeley and Hitch proposed to replace the concept of a unitary system with a tripartite system. This involves an attentional controller, the central executive, aided by two subsidiary slave systems, the visuo-spatial sketchpad, which holds and manipulates visual images, and the phonological or articulatory loop, which performs a similar function for speech-based information. It is this latter system that is assumed to be the principal determinant of immediate recall of digit sequences and that is defective in patients with short-term memory deficit. In neither the patients nor in the concurrent load study was there massive disruption of general performance, because performance could be maintained by the central executive and the visuo-spatial sketchpad. Although far from complete, this simple tripartite model has proved to be remarkably successful, both in accounting for a wide range of experimental data and in providing a useful framework for neuropsychological investigation. The three subsystems will be described in turn.

The Phonological Loop

This is the simplest and best understood of the three components. It is assumed to contain a temporary storage system in which acoustic or speech-based information can be held in the form of memory traces that spontaneously fade away within 2 or 3 sec unless refreshed by rehearsal. The rehearsal system is assumed to involve some form of subvocal articulation, which revives the memory trace, with the result that, given a small enough amount of information, it can be maintained indefinitely by continuous rehearsal. However, as the quantity increases the point is reached at which the first item has faded from memory before the last item has been processed, resulting in the limited capacity of memory span. Phonologically similar sequences such as the letters b, c, g, d, p are more error-prone, because the items have fewer phonological distinguishing features, making them more vulnerable to forgetting. The process of subvocal rehearsal is reflected in the word length effect, whereby a sequence of long words such as opportunity, tuberculosis, paramedical, refrigerator, university is substantially harder to recall than a sequence of five monosyllabic words. The processes of rehearsal and response production are assumed to operate in real time; longer words take longer to articulate, giving more time for the memory trace to fade.

A simple way of summarizing this lawful relationship is to observe that subjects can remember about as many words as they can say in 2 sec—short words or fast talking gives rise to long spans. Interestingly, the process of rehearsal does not need to be overt, since even patients who have lost the capacity to articulate as a result of a peripheral lesion may still show all the signs of subvocal rehearsal, including the word length effect (19). While there remains controversy over the extent to which the word length effect stems from the slowing of rehearsal versus the slowing of response output (20) and as to the exact nature of rehearsal in young children (21), the broad phenomena associated with the phonological loop appear to be well-established. Furthermore, the development of positron emission tomography scanning techniques has allowed the subcomponents to be identified with specific anatomical regions, with the phonological store apparently dependent upon the left perisylvian region, while the articulatory rehearsal system appears to reflect the operation of Broca's area (22, 23).

Although the two-component model appeared to give a good account of the available evidence, it remained unclear exactly what functional role was played by the phonological loop and why it had evolved in this way. Attempts to link it with language comprehension by studying the auditory sentence comprehension capacity of patients with a specific phonological loop deficit suggested some difficulties with particularly complex syntactic forms but failed to yield strong evidence for the phonological loop as a major component of comprehension (24), a conclusion that was consistent with the previously noted capacity of such patients to cope in everyday life with few apparent problems.

An alternative proposal was tested by Baddeley, Papagno, and Vallar (25), who suggested that the phonological loop might be necessary for new phonological learning, something of crucial importance for a child acquiring language but of much less significance for an adult, unless they are trying to learn a new language. The hypothesis was tested by requiring a patient with a very pure phonological memory deficit to learn a series of words in an unfamiliar language, Russian. While the patient showed no impairment in the capacity to learn to associate already familiar words, she was grossly impaired in learning Russian vocabulary. Subsequent studies showed that the capacity to hear and repeat back an unfamiliar pseudoword is an excellent predictor of the acquisition of new vocabulary, both in children acquiring both their first language (26) and their second (27). It appears to be the case, therefore, that the phonological loop has evolved as a crucial component of the system for language acquisition.

Visuo-Spatial Sketch Pad

While there is no doubt that a visuo-spatial parallel to the phonological loop exists, it has proved somewhat harder to investigate, due at least in part to its greater complexity. It seems likely, for example, that visual and spatial information are handled by separate but strongly interacting components of the system (28). It also seems likely that many uses of visual imagery are somewhat less practiced or automatic than the phonological coding that occurs for verbal information, and consequently tasks using the sketchpad often seem to place heavier demands on the central executive.

The initial experiments on the sketch pad utilized the technique whereby subjects were encouraged to use spatial imagery to encode a series of sentences for immediate recall. The procedure involves presenting the subject with a 4 × 4 matrix and designating one cell the starting square. The subject then hears a series of sentences, such as: In the starting square put a one, In the next square to the right put a two, In the next square to the right put a three, In the next square beneath put a four, In the next square to the right put a five, etc. Subjects invariably use imagery to encode the sentences in terms of a path through the matrix and can typically recall a sequence of eight sentences. The use of imagery can be avoided by replacing the spatial adjectives with nonspatial, such as good, bad, weak, and strong. Under these circumstances, subjects seem to rely on rote verbal rehearsal and can manage only about six sentences. When subjects were required to perform these two tasks at the same time as carrying out a spatial tracking task, analogous to steering a car on a winding track, performance on the imagery condition was markedly impaired, while the rote condition was unaffected, suggesting that imagery and tracking depend on a common visuo-spatial system (29). A later study contrasted visual and spatial interference effects. In one condition, subjects attempted to keep pointing at a moving sound source while blindfolded, a task involving spatial but not visual processing, while in another they made decisions about the brightness of a large screen, a task involving visual processing but minimal spatial demand. The imagery task was much more markedly impaired by the spatial interference. Subsequent research has, however, indicated that while the task described is principally a spatial one, others may be more visual in character (30).

It has been known since classical times that verbal memory may be enhanced by the use of visual imagery. Classical orators, for example, often remembered their speeches by imagining an iconic representative of each component, for example a sheaf of corn for the price of food, located at different points in a previously memorized building. Such visual encoding enhances memory, but can be interfered with by concurrent visual activity—for example, presentation of line drawings or patches of color which the subject is free to ignore (30)—or, as has recently been discovered, simply by exposing the subject to a constantly changing visual noise pattern (31). The visual noise has no effect on material that is dependent on rote verbal memory, which is, however, influenced by the concurrent presentation of speech or of patterned and fluctuating sounds, which influence phonological loop-based memory while having an effect on performance based on visual imagery.

Evidence for separate visual and spatial components of the sketch pad are also provided by neuropsychological studies. Patients have been described who show a pattern of disruption of spatial imagery, involved in activities such as image rotation or representation of locations or routes in space, while preserving the capacity to use imagery to make judgments about the shape or color of familiar objects, such as describing the shape of a dachshund's ears (32). Yet, other patients show the opposite pattern of disruption, with spatial impairment tending to be associated with lesions in the parietal lobes, whereas visual impairment is more commonly associated with occipital lobe damage (28, 33). More recently, positron emission tomography scanning studies have indicated at least four locations that are probably involved in the operation of the visuo-spatial sketch pad, including areas within the occipital, parietal, and frontal lobes (23). Finally, single unit recording in primates has begun to allow the careful tracing out of the areas involved in the temporary maintenance of visual information, producing data that are broadly compatible with the general working memory model, while providing considerably more anatomical detail (see ref. 34 in this issue of the *Proceedings* for a review of this area).

The study of the neurophysiological underpinning of the visuo-spatial sketch pad is therefore progressing rapidly, probably more so than is the case with the phonological loop; since animals tend not to indulge in verbal coding, the range of available physiological techniques is rather more narrow. At the psychological level, however, our understanding is probably rather less; we do not, for example, have a good conceptualization of the process of rehearsal, whereby visual material is maintained in the sketchpad. Furthermore, while one can speculate on plausible and necessary functions for the visuo-spatial sketch pad, relatively little work has been done so far on its everyday or evolutionary significance. Some of this comparative lack of progress has stemmed from the absence of clear behavioral methods of disrupting the separate components of the sketch pad. The Quinn and McConnell (31) visual noise technique described earlier seems highly promising in this regard and may well result in the rapid development of better interference techniques. Finally, it often appears to be the case that tasks that utilize the sketch pad, such as the use of imagery mnemonics, also rely heavily on the central executive, which, as we see below, is probably even more complex and less well-understood than the sketchpad.

The Central Executive

The central executive is assumed to be responsible for the attentional control of working memory. The concept was initially used principally as a holding operation, allowing the study of the more tractable problems of the slave systems, while accepting the need for further investigation of the complex processes that are almost certainly involved in the control of memory. The concept began to develop with the proposal by Baddeley (4) to link it to Norman and Shallice's (35) model of a supervisory attentional system, which they postulated to account for slips of action and for the complex pattern of symptoms observed in patients with frontal lobe damage. However, although agreeing that the central executive is likely to be heavily dependent upon the operation of the frontal lobes, Baddeley was careful not to define it anatomically, preferring to analyze the functions of the system first, only then asking the question of the anatomical substrate. The frontal lobes are large, complex, and almost certainly involve processes other than executive control; at the same time, executive processes are presumably a means of controlling varied regions of the brain, which suggests that they may be disrupted at points other than the frontal lobes. For that reason Baddeley and Wilson (36) proposed the term dysexecutive syndrome to refer to neuropsychological cases with disruption of executive functions that have often in the past been referred to as suffering from "frontal syndrome." (See ref. 37 for further discussion on this point.)

While it is possible that the central executive performs as a simple unitary controller, the variety and complexity of executive deficits in neuropsychological patients seems to point strongly in the direction of fractionation into subsystems or at least subprocesses. Our current strategy (38) is to attempt to identify such necessary executive processes and to develop methods of measurement and analysis, leaving for the future the question of whether such processes represent parts of a highly integrated system or a single executive, or whether the appearance of a single controller reflects the emergent properties of a series of parallel but equal processes, an executive "committee," perhaps?

Although we have begun to explore a range of executive processes (38), most progress has been made in one of these, the capacity to coordinate two or more concurrent activities. Our initial studies were prompted by an attempt to analyse the cognitive deficit in patients suffering from probable Alzheimer disease. In addition to the massive deficit in episodic long-term memory that is the principal hallmark of the disease, we found an impairment across a range of working memory tasks, which suggested a defective executive component rather than a deficit in the slave systems. We decided to investigate this by testing the capacity of the central executive to coordinate activity in the two slave systems.

The experimental design involved comparing three groups of subjects, probable Alzheimer disease patients, normal elderly subjects, and normal young subjects. In a typical study, the phonological loop would be occupied by a digit span task, and the sketch pad would be occupied by visuo-spatial tracking. In both cases, task difficulty was titrated to a point at which all three groups were operating at an equivalent level when the tasks were performed independently. When required to track and remember digits simultaneously, the young and elderly showed a small and equivalent decrement, whereas that shown by the probable Alzheimer disease patients was substantially greater (39). A subsequent longitudinal study demonstrated that the capacity of probable Alzheimer disease patients to coordinate tasks deteriorated much more dramatically than performance on the tasks performed alone (40).

A recent positron emission tomography scanning study (41) suggests that dual-task performance does indeed involve frontal lobe function, although that does not, of course, imply that all patients with damage anywhere in the frontal lobes will perform poorly at dual-task coordination. This view is supported by a study analyzing the dual-task performance of a group of 24 patients with well-established frontal lobe lesions. The patients were also tested on two standard "frontal" measures, namely the Wisconsin Card Sorting Test (42), a concept formation task in which patients with frontal damage tend to perform poorly and perseverate on earlier solutions, and verbal fluency, a task in which subjects try to generate as many items as possible from a given category such as animals, which again is often impaired in patients with frontal lobe damage (42). Finally we were interested in attempting to capture the behavioral disorder that accompanies the classic frontal syndrome, often reflected in disinhibition or apathy. We based our measure of this on clinical ratings by two independent judges, one relying on observations during neuropsychological testing of the patients, while the other reflected comments by the patient's carer. While all subjects showed a broad tendency to deterioration on the card sorting and verbal fluency tests, neither of these was significantly associated with behavioral disturbance. On the other hand, those patients who showed behavioral signs performed significantly worse on dual-task performance than those whose behavior was comparatively normal (43).

Although the association between dual-task performance and conduct was serendipitous, it does bear a resemblance to an independent finding by Alderman (44), who carried out a study concerned with a rehabilitation program for brain damaged patients with behavioral problems. While the program was in general successful, a substantial minority of patients failed to benefit. In testing these patients on a wide range of measures, one cluster of tests proved to be particularly revealing, namely those involving the need to coordinate two tasks, on which consistently poor performance was shown by patients who failed to respond to the rehabilitation program.

These two studies observing a link between dual-task performance and behavior are highly intriguing, but should clearly be replicated before drawing strong conclusions. If they do replicate, they present the problem as to why the association should occur. One possibility is that of a similar anatomical localization of two separate processes. A more interesting possibility, however, might relate to the role of multitask coordination in social behavior; perhaps the need to maintain one's own interests at the same time as paying attention to those around places heavy demands on the capacity for dual-task performance?

While this approach to the analysis of the central executive is still at a relatively early stage, there has been some progress in postulating and beginning to study other candidate executive processes, including the capacity to focus attention, to switch attention from one focus to another, and to use working memory to activate aspects of long-term memory (38). There has also been considerable interest in exploring the function of working memory, typically by developing measures of individual difference in working memory capacity, and relating these to performance on tasks, such as comprehension, reasoning, and general intelligence tests.

One of the most extensively used measures was that developed by Daneman and Carpenter (45), who defined a working memory task as one that simultaneously required the storage and manipulation of information. The task they use most frequently is termed working memory span and involves presenting the subject with a series of sentences. After reading them, the subject must recall the last word of each sentence; span is set by the maximum number of sentences the subject can both read and recall the final words. Daneman and Carpenter found that performance on this test predicted prose comprehension skills in their college student subjects, going on to observe in more detail the way in which working memory capacity appears to underpin such components of comprehension as capacity to draw inferences and to extrapolate beyond the evidence given (46).

Using a similar paradigm, Oakhill, Yuill, and Parkin (47) have studied children who appear to be reasonably good at reading, in the sense of pronouncing written words, but poor at comprehending the prose that they read. Such children tend to have low working memory spans, leading Oakhill *et al.* to suggest that they have a deficit in central executive capacity.

Both they and Turner and Engle (48) find that it is not necessary to incorporate sentential material in the span measure; for example, a sequence of calculations followed by unrelated words appears to predict subsequent comprehension virtually as well.

Using a similar definition of working memory, namely the capacity to simultaneously store and process information, Kyllonen and Christal (49) attempted to relate working memory measures to more traditional intelligence tests, typically based on reasoning tasks. They observed a high correlation between the two sets of measures, with the working memory tests depending slightly more on speed of processing, and the intelligence tests being more influenced by prior experience and education. This latter point is important in certain selection situations, where, for example, it may be necessary to evaluate the job potential of people from a range of different cultural and educational backgrounds. The practical value of working memory measures is demonstrated by a study in which Christal (50) found that he was able to predict success in a course on logic gates more effectively on the basis of the working memory battery than on the basis of more traditional psychometric tests.

In conclusion, the development of the concept of a unitary short-term memory store into that of a multicomponent working memory system has proved extremely fruitful, both in theoretical and applied research. Working memory provides a crucial interface between perception, attention, memory, and action. As an area that has already proved the value of combining the methods and concepts of cognitive psychology with those of neurobiology, working memory seems likely to continue to play a lively and productive role in the developing discipline of cognitive neuroscience.

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1. Atkinson, R. C. & Shiffrin, R. M. (1968) in *The Psychology of Learning and Motivation: Advances in Research and Theory*, ed. Spence, K. W. (Academic, New York), Vol. 2, pp. 89–195.
2. Olton, D. S. (1979) *Am. Psychol.* **34,** 583–596.
3. Newell, A. & Simon, H. A. (1972) *Human Problem Solving* (Prentice–Hall, Englewood Cliffs, NJ).
4. Baddeley, A. D. (1986) *Working Memory* (Oxford Univ. Press, Oxford).
5. Hebb, D. O. (1949) *Organization of Behavior* (Wiley, New York).
6. Brown, J. (1958) *Q. J. Exp. Psychol.* **10,** 12–21.
7. Peterson, L. R. & Peterson, M. J. (1959) *J. Exp. Psychol.* **58,** 193–198.
8. Melton, A. W. (1963) *J. Verbal Learn. Verbal Behav.* **2,** 1–21.
9. Glanzer, M. & Cunitz, A. R. (1966) *J. Verbal Learn. Verbal Behav.* **5,** 351–360.
10. Conrad, R. (1960) *Br. J. Psychol.* **51,** 45–48.
11. Baddeley, A. D. (1966) *Q. J. Exp. Psychol.* **18,** 362–365.
12. Baddeley, A. D. (1966) *Q. J. Exp. Psychol.* **18,** 302–309.
13. Milner, B. (1966) in *Amnesia*, Whitty, C. W. M. & Zangwill, O. L. (Butterworth, London), pp. 109–133.
14. Zangwill, O. L. (1946) *Br. J. Psychol.* **37,** 8–19.
15. Baddeley, A. D. & Warrington, E. K. (1970) *J. Verbal Learn. Verbal Behav.* **9,** 176–189.
16. Shallice, T. & Warrington, E. K. (1970) *Q. J. Exp. Psychol.* **22,** 261–273.
17. Craik, F. I. M. & Watkins, M. J. (1973) *J. Verbal Learn. Verbal Behav.* **12,** 599–607.
18. Baddeley, A. D. & Hitch, G. (1974) in *The Psychology of Learning and Motivation*, ed. Bower, G. A. (Academic, New York), Vol. 8, pp. 47–89.
19. Baddeley, A. D. & Wilson, B. (1985) *J. Mem. Lang.* **24,** 490–502.
20. Cowan, N., Day, L., Saults, J. S., Keller, T. A., Johnson, T. & Flores, L. (1992) *J. Mem. Lang.* **31,** 1–17.
21. Gathercole, S. E. & Hitch, G. (1993) in *Theories of Memory*, eds. Collins, A. F., Gathercole, S. E., Conway, M. A. & Morris, P. E. (Lawrence Erlbaum, Sussex, U.K.), pp. 189–210.
22. Paulesu, E., Frith, C. D. & Frackowiak, R. S. J. (1993) *Nature (London)* **362,** 342–345.
23. Jonides, J., Smith, E. E., Koeppe, R. A., Awh, E., Minoshima, S. & Mintun, M. A. (1993) *Nature (London)* **363,** 623–625.
24. Vallar, G. & Shallice, T., eds. (1990) *Neuropsychological Impairments of Short-Term Memory* (Cambridge Univ. Press, Cambridge, U.K.).
25. Baddeley, A. D., Papagno, C. & Vallar, G. (1988) *J. Mem. Lang.* **27,** 586–595.
26. Gathercole, S. & Baddeley, A. D. (1989) *J. Mem. Lang.* **28,** 200–213.
27. Service, E. (1992) *Q. J. Exp. Psychol.* **45A,** 21–50.
28. Farah, M. J. (1988) *Psychol. Rev.* **95,** 307–317.
29. Baddeley, A. D., Grant, S., Wight, E. & Thomson, N. (1973) in *Attention and Performance V*, eds. Rabbitt, P. M. A. & Dornic, S. (Academic, London), pp. 205–217.
30. Logie, R. H. (1986) *Q. J. Exp. Psychol.* **38A,** 229–247.
31. Quinn, J. & McConnell, J. (1996) *Q. J. Exp. Psychol.* **49A,** 200–215.
32. Farah, M. J., Hammond, K. M., Levine, D. N. & Calvanio, R. (1988) *Cognit. Psychol.* **20,** 439–462.
33. Hanley, J. R., Young, A. W. & Pearson, N. A. (1991) *Q. J. Exp. Psychol.* **43A,** 101–126.
34. Goldman-Rakic, P. S. (1996) *Proc. Natl. Acad. Sci. USA* **93,** 13473–13480.
35. Norman, D. A. & Shallice, T. (1980) *Attention to Action: Willed and Automatic Control of Behavior* (University of California San Diego, La Jolla, CA), CHIP Report 99.
36. Baddeley, A. D. & Wilson, B. (1988) *Brain Cognit.* **7,** 212–230.
37. Baddeley, A. D. & Della Sala, S. (1996) *Proc. R. Soc. London*, in press.
38. Baddeley, A. D. (1996) *Q. J. Exp. Psychol.* **49A,** 1, 5–28.
39. Baddeley, A. D., Logie, R., Bressi, S., Della Sala, S. & Spinnler, H. (1986) *Q. J. Exp. Psychol.* **38A,** 603–618.
40. Baddeley, A. D., Bressi, S., Della Sala, S., Logie, R. & Spinnler, H. (1991) *Brain* **114,** 2521–2542.
41. D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S. & Grossman, M. (1995) *Nature (London)* **378,** 279–281.
42. Milner, B. (1964) in *The Frontal Granular Cortex and Behavior*, eds. Warren, J. M. & Akert, K. (McGraw–Hill, New York), pp. 313–334.
43. Baddeley, A. D., Della Sala, S., Papagno, C. & Spinnler, H. (1996) *Neuropsychology*, in press.
44. Alderman, N. (1996) *Neuropsychol. Rehabil.* **6,** 161–186.
45. Daneman, M. & Carpenter, P. A. (1980) *J. Verbal Learn. Verbal Behav.* **19,** 450–466.
46. Daneman, M. & Carpenter, P. A. (1983) *J. Exp. Psychol. Learn. Mem. Cognit.* **9,** 561–584.
47. Oakhill, J. V., Yuill, N. & Parkin, C. (1988) in *Practical Aspects of Memory: Current Research and Issues*, eds. Gruneberg, M. M., Morris, P. E. & Sykes, R. N. (Wiley, Chichester, U.K.), Vol. 2, pp. 315–320.
48. Turner, M. L. & Engle, R. W. (1989) *J. Mem. Lang.* **28,** 127–154.
49. Kyllonen, P. C. & Christal, R. E. (1990) *Intelligence* **14,** 389–433.
50. Christal, R. E. (1991) *Comparative Validities of ASVAB and LAMP Tests for Logic Gate Learning* (Armstrong Laboratory, Human Resources Directorate, Brookes Airforce Base, TX), Tech. Rep. A.L.-T.P.-1991-0031.