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Short-Term and Working Memory

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The study of short-term memory, the retention of small amounts of information over brief time intervals, formed a major component of the development of cognitive psychology during the 1960s. It had a strong theoretical component, derived from the increasingly influential computer metaphor, combined in Britain at least with a concern for application to problems such as those of air traffic communication (Broadbent, 1958) and of coding in telephony and postal systems (Conrad, 1964). The attempt to develop information-processing models of short-term memory (STM) led to some major controversies (see below). Unfortunately, resolving these issues unequivocally proved beyond the capability of the methods available at the time, resulting in a decline of interest in STM during the 1970s, and subsequently even to a declaration of its demise (Crowder, 1982).

However, as the old concept of STM was losing favor, it became incorporated within a more complex framework, *working memory* (WM), which proposed that the older concept of a unitary store be replaced by a multicomponent system that utilized storage as part of its function of facilitating complex cognitive activities such as learning, comprehending, and reasoning (Baddeley & Hitch, 1974). Interest in WM continued to develop through the 1980s, though with somewhat different emphases on different sides of the Atlantic. During the 1990s, the whole area has received a further boost from the development of functional imaging techniques, with the components of working memory offering an appropriate level of complexity for the developing techniques of brain scanning. This development was facilitated by the very fruitful relationship between cognitive psychology and the neuropsychology of working memory, which provided hypotheses as to which areas of the brain might be most likely to be involved in particular tasks, together with concepts that facilitate the linking of the neuroanatomy to a coherent cognitive framework. Finally, and coincidentally, some of the old applied problems are now beginning to resurface. In both the United States and Britain, for example, there is currently considerable concern about the best way to extend the ever-expanding series of telephone codes so as to optimize capacity without unduly increasing length, while new areas such as pharmaceutical prescribing errors are beginning to highlight the need for an understanding of the processes involved, and to draw upon the empirical work of the 1960s (Lambert, 1997).

As a result of these various developments, there is a growing interest in the field of STM and WM from scientists whose principal training has been in other areas, but who wish to incorporate measures of short-term and working memory into their work. Finally, the area continues to attract good young researchers who see the study of working memory as an important interface between research on memory, perception, and attention.

While there are many overviews of the area, ranging from the relatively brief (Baddeley, 1992) to the chapter length (Baddeley, 1996) and the book length (Gathercole, 1996; Miyake & Shah, in press), neither these nor journal articles tend to include the sort of practical detail that is so important if one wishes to carry out or evaluate experiments. The present chapter aims to go some way toward filling this gap, while bearing in mind that the only way to fully understand a technique is to use it. Here STM and WM are treated separately, since the relevant techniques, driven by the specific theoretical issues of the time, tend to be somewhat different. However, it is important to bear in mind that they do form part of the same tradition, and that it is increasingly common for 1960s techniques and methods to find new uses in the 1990s. It may be useful, however, to begin with some terminology.

Terminology

The division of memory into two or more systems was proposed by William James (1890), who distinguished between *primary memory*, which he regarded as closely associated with conscious awareness, and *secondary memory*, which referred to more durable memories. When the interest in fractionating memory revived in the late 1950s, the term STM was used to refer to tasks in which small amounts of material were retained over brief intervals, in contrast to LTM, which involved retention over more than a few seconds. It subsequently became clear that performance on STM tasks was not a pure reflection of the hypothetical underlying system, but was also influenced by LTM. To avoid confusion, some investigators used different terms to refer to the hypothetical underlying theoretical memory systems, such as *short-term* and *long-term store* (STS and LTS: Atkinson & Shiffrin, 1968), or reverting to *primary* and *secondary memory* (Waugh & Norman, 1965).

In recent years, the term *working memory* proposed by Miller, Galanter, and Pribram (1960) has been developed to emphasize the functional role of STM as part of an integrated system for holding and manipulating information during the performance of complex cognitive tasks (Baddeley & Hitch, 1974). Unfc tunately, the same term has been us independently within the animal learning l erature, where it refers to situations in whi the animal needs to retain information acro several trials during the same day (Olto Walker, & Gage, 1978), almost certainly i volving different mechanisms from those i volved in the typical human WM task. Finall the production system approach to comput tional modeling proposed by Newell and S mon (1972) postulates a working memory unlimited capacity, although this is not a sumed to be related to the limited capaci STM system proposed by experimentalis such as Baddeley and Hitch (1974). Fort nately, the context is usually sufficient avoid too much confusion between the var ous users of the term.

Short-Term Memory

Methods and Techniques

Before going on to discuss recent theoretic developments in the area, it may be useful t describe some of the rich armament of meth ods and techniques that have been develope to study verbal and visual STM.

Verbal STM

Memory Span

Subjects are presented with a sequence c items, which they attempt to reproduce in th presented order. Typically, digits, consonant or words are used. Presentation may be visua or auditory, with auditory presentation tenc ing to give a slight advantage, particularl over the last one or two items, the so-calle *modality effect*. Rates of presentation typicall range from 0.5s to 2s per item, with 1s proba bly being the commonest. Presentation rate i not a major variable within this range, bu faster rates run the risk of errors owing to fail ure to perceive, while slower rates give suffi cient time for subjects to engage in comple and often highly variable rehearsal strategies.

Recall may be spoken or written. It is usua to require the subject to recall in the order o presentation, and to monitor that this is th case. Performance is typically measured ir terms of the maximum level achieved, wit span formally being the point at which th subject recalls the ordered sequence of item on 50% of occasions. This is not easy to determine directly, and hence a number of approximations are used. One simple method is to take the mean of the length of the three longest sequences correctly recalled, so a subject being correct on three out of four 7-item sequences, and one at length eight, would have a score of 7.33.

Memory span has the disadvantage that many of the data collected come from sequence lengths at which performance is perfect, hence providing little information. More information may be gained from using a procedure in which all sequences are presented at the same length, which should be at or slightly beyond span. Performance can then be scored either in terms of number of *sequences* completely correct or of number of *items* recalled in the correct serial position.

In his classic paper *The magic number seven*, George Miller (1956) speculated that in the area of absolute perceptual judgments, subjects could typically distinguish about 7 separate categories, while a typical digit span was about 7 items. He went on to emphasise that this latter conclusion was a gross oversimplification since it was possible to increase this substantially by *chunking*, a process whereby several items are aggregated into a larger super item. Perhaps the clearest demonstration of this is in immediate memory for prose material; memory span for unrelated words is about 5 or 6, whereas with meaningful sentences, spans of 16 words or more are not unusual (Baddeley, Vallar, & Wilson, 1987). Syntax and meaning make prose highly redundant, and an early paper by Miller and Selfridge (1950) showed that the more closely a string of words approximates to English prose, the longer the memory span. However, although absolute number of words increases with approximation to English, Tulving and Patkau (1962) showed that the number of chunks remains constant.

Free Recall

This simple task involves presenting the subject with a list, typically of words, that subjects attempt to recall in any order they wish. The classic serial position curve shows excellent recall of the last few items (the *recency effect*), somewhat better recall of the first one or two items (the *primacy effect*), and a relatively flat function between.

A brief filled delay will wipe out the recency effect while having little effect on earlier items. Virtually any variable that will influence long-term learning (e.g., rate of presentation, familiarity of material, the presence of a secondary task, or the age of the subject) will influence earlier items but have little or no impact on the recency effect (Glanzer, 1972). The recency effect reflects a strategy of first recalling the earlier items, and is abolished if subjects are dissuaded from this. It appears to be a very basic and robust strategy that is found in young children, amnesic patients, and even patients suffering from Alzheimer's disease (Glanzer, 1972; Baddeley & Hitch, 1993).

The primacy effect is less marked and less robust. It may reflect a number of variables, but in particular the tendency to give more attention and possibly more rehearsal to the initial item (Hockey, 1973).

While the typical serial position function operates across a wide range of lengths and presentation rates, most experimenters avoid sequences of less than 10 items, since there is a tendency for subjects to attempt to recall short sequences in serial order. Presentation rate is typically slower than in memory span, since this increases the amount of recall from the earlier long-term part of the curve, with 2s per item being the most common presentation rate. It is also not uncommon to use semantically categorized material, since this again increases performance and also gives some indication as to whether the subject is able to take advantage of meaning (Tulving & Pearlstone, 1966).

Short-Term Forgetting

The classic paradigm here was developed by Peterson and Peterson (1959); their subjects were presented with three consonants and required to retain them over a delay ranging from 0–18s, during which they counted backwards in threes. Performance reflects an STM component that declines over about 5 seconds (Baddeley & Scott, 1971), and an LTM component reflecting the extent to which items can be discriminated from prior items, the result of *proactive interference* (PI; Keppel & Underwood, 1962). PI can be prevented by changing the type of material to be remembered—for example, switching from animals to flowers (Wickens, 1970) or by inserting a delay between successive trials (Loess & Waugh, 1967), resulting in a recovery of performance (*release from PI*), followed by a further buildup of PI.

Memory Probe Techniques

The act of recalling an item can itself produce forgetting, either because the time taken to recall allows further trace decay or because the recall process disrupts the memory trace. One way of avoiding both of these is through probe techniques, whereby only part of the remembered material is sampled. For example, Sperling (1963) presented subjects with 3 rows of 4 letters. At recall, one of the 3 rows is cued by a tone. Since the subject does not know in advance which row, one can legitimately multiply that score by the number of rows to estimate the capacity of the memory system, which is typically greater than that obtained using more standard total recall methods. In a variant of this, Waugh and Norman (1965) presented their subjects with a series of digit strings varying in length. The experimenter then provided one item from the string and required the subject to produce the next in sequence. Recall performance showed a very clear recency effect, which was minimally affected by rate of presentation, suggesting that forgetting was principally due to the limited capacity of the short-term store rather than to temporal trace decay.

A variant of the memory probe technique was developed by Sternberg (1966), who used speed of response as a means of investigating the storage of items within the memory span. A digit list ranging in length from 1 to 6 was presented, followed by a probe digit. The task was to decide whether the probe digit had been part of the previously presented sequence. Reaction time increased linearly with the length of the presented sequence. This occurred not only for positive probes but also for negative probes, where the item had not been in the list. Sternberg proposed a model based on the analogy of a computer serially scanning its memory store, with the slope of the function relating RT to number items in store providing a measure of hypothetical scanning rate, typically about 40 ms per item. The fact that slopes for "yes" and "no" responses were the same prompted Sternberg to suggest that the search was exhaustive. If subjects could respond as soon as they detected a match with the probe, then the "yes" response slope should be shallower than the "no." This led to intensive experimental work that uncovered phenomena inconsistent with the scanning model, such as effects of recency (Corballis, Kirby, & Miller, 1972) and repetition effects (Baddeley & Ecob, 1973), leading to the proposal of alternative models (Anderson, 1973; Theios, 1973). With the growth in number of models and a lack of crucial experimental evidence, the technique became unfashionable, although it is still quite extensively used as a measure of cognitive deficit following drugs or stressors, for which it provides a neat and reasonably sensitive measure. In the absence of any broadly accepted theoretical interpretation, it continues to offer a theoretical challenge.

Nonverbal STM

Research on STM was dominated by verbal tasks, probably because the material is so easy to manipulate and record. However, analogous effects have been shown for visual memory. Dale (1973) required subjects to remember the location of a single point on an open field over a delay filled by verbal counting, finding that accuracy declined steadily over time. Phillips (1974) presented subjects with a matrix of which half the cells were filled, presenting a second matrix for recognition after a filled delay varying in length. Performance remained high over the delay for simple 2 × 2 matrices, with forgetting becoming steeper as the complexity of the matrix increased. In a subsequent study, Phillips and Christie (1977) presented subjects with a sequence of matrix patterns, observing that only the last pattern showed evidence of excellent initial performance followed by rapid decay, while earlier matrices showed a low level of performance. This pattern of results, therefore, suggests a short-term visual memory store that is limited to one pattern, with performance on that pattern being a function of its complexity. This has been used to develop a measure of pattern span in which the subject is shown a pattern and attempts to reproduce it on a matrix. The test begins with a 2 × 2 matrix with half the cells filled, increasing to a point at which the subject is no longer able to accurately reproduce the pattern, which for a normal adult is typically around 16 cells (Della Sala, Gray, Baddeley, & Wilson, 1997).

An alternative measure of visuo-spatial span is the Corsi block tapping task (Milner, 1968), in which the subject is faced with an array of 9 quasi-randomly arranged blocks. The experimenter taps a particular sequence of blocks and asks the subject to imitate, starting with just 2 and building up to a point at which performance breaks down, typically around 5 taps. This task has a sequential and motor component missing from the pattern span, and appears to measure a different aspect of visuo-spatial memory, since patients can be impaired on one but not the other; furthermore, spatial activity interferes with Corsi span, while intervening abstract pictures differentially interferes with pattern span (Della Sala, Gray, Baddeley, Allamano, & Wilson, in press).

Memory for location using a technique somewhat similar to that developed by Dale suggests that visual and verbal STM involve different brain regions (Smith & Jonides, 1995) and also that the maintenance of even a single item involves an active process involving the frontal lobes (Goldman-Rakic, 1996; Haxby, Ungerleider, Horwitz, Rapoport, & Grady, 1995).

Research on other nonverbal retention is less well developed, but studies of memory for kinaesthetic stimuli (Adams & Dijkstra, 1966) and tactile stimuli (Gilson & Baddeley, 1969) show rapid forgetting over a short delay, whereas memory for odors (Engen, Kuisma, & Eimas, 1973) does not.

Theoretical Issues

Despite earlier suggestions that there might be more than one kind of memory (Hebb, 1949; James, 1890), the issue was largely ignored until the discovery of the short-term forgetting of small amounts of information over filled intervals by Brown (1958) and Peterson and Peterson (1959), which led the investigators to propose separate LTM and STM memory systems, with short-term forgetting reflecting the spontaneous decay of the memory trace. This view was resisted, notably by Melton (1963), who argued strongly for a unitary memory system in which forgetting reflected associative interference between the items retained, rather than trace decay. The importance of PI in the STM paradigm (Keppel & Underwood, 1962) suggested that interference effects certainly occur in STM, although these in turn could be interpreted as reflecting limited capacity, rather than classic associative interference (Waugh & Norman, 1965). The issue of whether short-term forgetting reflects decay or interference remains unresolved.

During the mid-1960s proponents of a dichotomy between STM and LTM generated evidence from a range of sources, including:

Two Component Tasks: Tasks such as free recall appear to have separate components, with the recency effect reflecting STM, while earlier items appear to depend upon LTM (Glanzer, 1972).

Acoustic and Semantic Coding: Conrad (1962) showed that errors in recalling visually presented consonants tended to be similar in sound to the correct items (e.g., *B* is remembered as *V*), suggesting that recall is based on an acoustic code. Baddeley (1966a, 1966b) showed that immediate recall sequences of 5 unrelated words was highly susceptible to acoustic similarity but insensitive to semantic similarity, while delayed recall of 10-word lists showed exactly the opposite pattern. Using a probe technique, Kintsch and Buschke (1969) showed that the recency part of the function reflected acoustic similarity effects, while performance on earlier items reflected semantic coding. These studies, therefore, appeared to suggest a predilection for acoustic coding in STM and semantic coding in LTM.

Neuropsychological Evidence: Amnesic patients such as the classic case HM (Milner, 1966) showed grossly impaired LTM, together with preserved span. Such patients also showed preserved recency, and if intellectually otherwise intact, normal performance on the Peterson Short-Term Forgetting Task (Baddeley & Warrington, 1970). In contrast, a second class of patient appeared to show the opposite pattern with digit spans of 1 or 2 items, very poor Peterson performance, and little or no recency, coupled with apparently normal LTM (Shallice & Warrington, 1970). This double dissociation strongly supported a separation of LTM and STM.

By the late 1960s, a range of models began to appear in which STM and LTM were conceptualized as separate systems. The most influential of these was the Atkinson and Shiffrin (1968) model, which became known as the *modal model*. As shown in figure 5.1, it assumes that information comes in from the environment through a parallel series of sensory memory systems into a limited-capacity short-term store, which forms a crucial bottleneck between perception and LTM. The STS was also assumed to be necessary for recall, and to act as a limited-capacity working memory.

In the early 1970s, the modal model encountered two major problems. The first concerned its assumptions regarding long-term learning, while the second involved its capac-

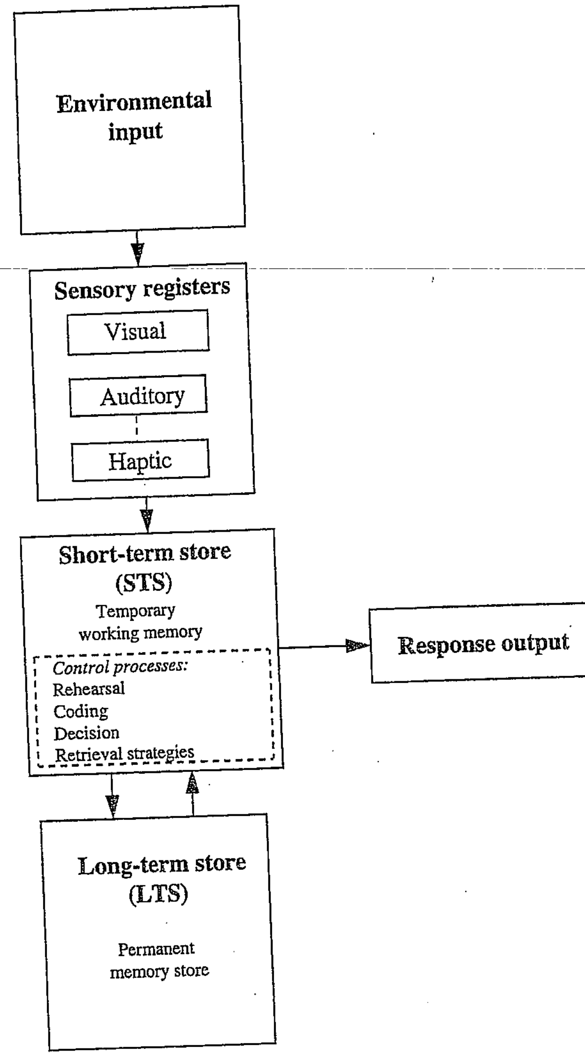

Figure 5.1 Atkinson & Shiffrin's (1968) influential model of STM.

ity to explain the neuropsychological evidence.

The modal model assumed that the longer an item was held in STS, the greater the chance of its being transferred to the LTS. This assumption was challenged (e.g., Craik & Watkins, 1973), leading Craik and Lockhart (1972) to propose their levels of processing hypothesis. This proposes that the durability of memory increases with depth of processing, hence processing a word in terms of its visual appearance leads to little learning. Phonological processing in terms of sound is somewhat better, whereas deeper semantic processing leads to the best retention. While the detailed application of this model can be criticized (Baddeley, 1978), there is no doubt that it represents a good account of a considerable amount of data, and that the underdevelopment of its treatment of coding represents a limitation of the modal model.

The second problem with the modal model stems from its apparent prediction that patients with a grossly impaired STS should encounter associated problems in long-term learning. Furthermore, since the STS was assumed to act as working memory, allowing complex information processing to proceed, then such patients should also have major general information-processing deficits. However, the few relatively pure cases studied appeared to have normal long-term memory and to lead largely normal lives (Shallice & Warrington, 1970; Vallar & Shallice, 1990).

Working Memory

In order to tackle this problem, Baddeley and Hitch (1974) proposed that the concept of a single unitary STM be replaced by a multi-component system, focusing on three subsystems. These comprised two slave systems; one, the *phonological loop* was concerned with storing acoustic and verbal information, while the second, the *visuo-spatial sketchpad*, was its visual equivalent (see figure 5.2). The overall system was assumed to be controlled by a limited-capacity attentional system, the *central executive*. While the details of this model and its terminology are by no means universally accepted, the last 20 years have seen an increasing tendency for the term *working memory* to be used, together with a broad general acceptance of the usefulness of postulating a system that combines executive control with more specialized storage systems that show important differences between visual and verbal material (Miyake & Shah, 1999). For that reason, the tripartite structure will be used as a basis for the review, while accepting that there may be a subsequent need to postulate other components.

Verbal Working Memory

This system, labeled by Baddeley and Hitch the *articulatory* or *phonological loop*, is closest in character to the original concept of a short-term store. It is assumed to be defective in the type of patient studied by Shallice and Warrington (1970). The general cognitive disruption implied by the modal model does not occur because the central executive is intact in such patients. The phonological loop is assumed to comprise two components, a store in which an acoustic or phonological memory trace is held. The trace is assumed to decay within about two seconds unless performance is maintained by the second component, the process of subvocal articulatory rehearsal. This process is not only able to refresh the memory trace but can also register visually presented but nameable material in the phonological store by means of articulation. The principal evidence for phonological coding is the previously described acoustic similarity effect, while the role of the articulatory process is supported by the *word length effect*, whereby the immediate memory span for words is a direct function of the length of the constituent items. A simple rule of thumb is that subjects can remember as many items as they can say in two seconds (Baddeley, Thompson, & Buchanan, 1975). Baddeley and Hitch explained this phenomenon in terms of trace decay, proposing that subvocal maintenance rehearsal occurs in real time, hence long words take longer to rehearse, allowing

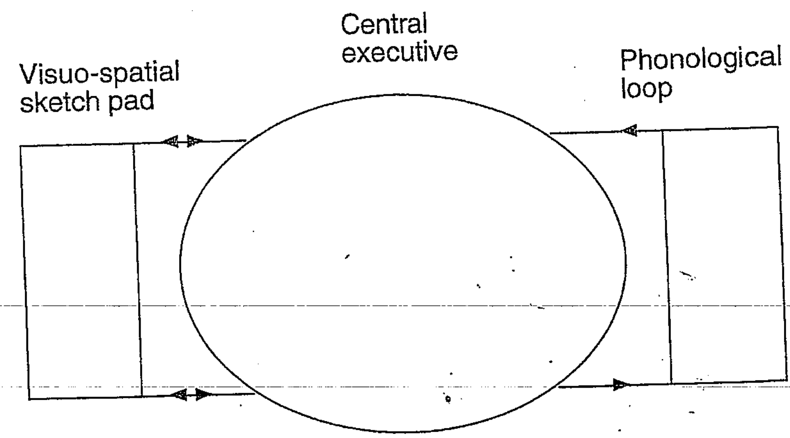

Figure 5.2 The Working Memory model proposed by Baddeley & Hitch (1974).

more forgetting through trace decay. Cowan et al. (1992) suggest that the word length effect principally is a function of forgetting during the process of recall, with longer words taking longer to produce, hence allowing more decay. As the effect can also be found, though to a lesser extent, with probed recall, it seems likely that both rehearsal rate and output time contribute to the word-length effect (Avons, Wright, & Pammer, 1994).

Articulatory suppression is a procedure whereby the subject is required to utter some repeated redundant sound such as the word "the" while performing another task such as memory span. Murray (1968) showed that suppression reduces performance and also eliminates the phonological similarity effect, with visual, though not with auditory, presentation. This is assumed to occur because suppression prevents the subject from converting the visual stimulus into a verbal code that is suitable for registering in the phonological store. With auditory presentation, access to the store is assumed to be automatic (Baddeley, 1986). The effect of suppression on the word-length effect is assumed to be somewhat different. Since the word-length effect is a direct function of rehearsal, suppression will remove the effect, regardless of whether presentation is auditory or visual, as indeed is the case (Baddeley, Lewis, & Vallar, 1984).

Another area of considerable activity and controversy in connection with the word-length effect relates to individual differences. If trace decay is responsible for the word-length effect, then subjects who rehearse more slowly should show poorer performance. This was indeed found by Baddeley et al. (1975). Nicolson (1981) observed that developmental changes in children's memory span were associated with changes in speed of articulation, suggesting that faster rehearsal might be responsible for the increase in span with age. The effect was replicated by subsequent studies (e.g., Hitch, Halliday, Dodd, & Littler, 1989), while research on serial recall of pictured objects suggested that verbal coding was a strategy that children begin to adopt between the ages of 7 and 10, as reflected by the influence on performance of the acoustic similarity of the names in the set and of their spoken length (Hitch, Halliday, Schaafstad, & Hefferman, 1991). Younger children appear to use some form of visual code, and hence perform more poorly when the items depicted are similar in shape—for example, a spoon, a pen, and a twig.

When material is presented auditorily, phonological similarity and word-length effects appear at a much earlier age, a result which was initially taken to suggest that rehearsal begins at this early stage. However, opinion is now shifting toward the assumption that this very early rehearsal reflects a different and relatively automatic process—more like a spontaneous internal echoing of the stimulus than a coherent cumulative rehearsal strategy such as is found in older children and adults (Gathercole & Hitch, 1993).

Finally, there has been considerable interest in recent years in the possible evolutionary function of the phonological loop; if patients can show gross impairment in memory span with little impact on everyday functioning, can the loop be of much biological significance? Initial work focused on the possible role of the loop in language comprehension (Vallar & Baddeley, 1984). Although there are some differences among patients, the general consensus is that most have difficulty only when syntactic structures require the literal maintenance of the first part of the sentence until it is disambiguated at the end, as for example in the case of self-embedded sentences (see Vallar & Shallice, 1990, for a review).

A much stronger case for the importance of the phonological loop can be made in the case of new phonological learning. For example, PV, a patient with a very pure STM deficit, showed no difficulty in learning to associate pairs of words in her own language, but was grossly impaired in capacity to learn the vocabulary of an unfamiliar language, Russian (Baddeley, Papagno, & Vallar, 1988). In a subsequent study, Gathercole and Baddeley (1990) found that children with a specific language disability were particularly impaired in their capacity to hear and repeat back unfamiliar sound sequences. This deficit was more pronounced than their language impairment and did not appear to be attributable to either perceptual or speech production problems. This work led to the development of a nonword repetition test in which the subject attempts to repeat spoken nonwords ranging in length from 2 syllables (e.g., *ballop*) to 5 (e.g., *voltularity*). Nonword repetition performance proved to correlate with level of vocabulary development across a wide range of ages; over the 4- to 5-year range, cross-lagged correlation suggested that nonword repetition was causally related to the subsequent development of vocabulary, rather than the reverse (see Baddeley, Gathercole, & Papagno, 1998, for a review). Finally, the phonological short-term store appears to be related to the capacity for second-language acquisition in both children (Service, 1992) and adults (Papagno, Valentine, & Baddeley, 1991), with variables such as articulatory suppression, phonological similarity, and word length all influencing the acquisition of novel word forms but not affecting the capacity to associate pairs of already familiar words, a process that is assumed to depend principally on semantic coding (Papagno & Vallar, 1992).

Neurobiological Evidence

Neuropsychological studies of STM patients suggested an impaired phonological store (Vallar & Baddeley, 1984; Vallar & Shallice, 1990). The capacity to articulate overtly is not necessary for rehearsal since dysarthric patients with a peripheral disruption to speech production appear to have normal rehearsal capacities (Baddeley & Wilson, 1985). However, dyspraxia, a disruption of the basic capacity to program speech output, does interfere with memory performance (Waters, Rochon, & Caplan, 1992).

More recently, functional imagery studies using PET and fMRI have produced clear evidence for a phonological short-term store located in the perisylvian region of the left hemisphere, together with a separate rehearsal component associated with Broca's area (Paulesu, Frith, & Frackowiak, 1993; Awh et al., 1996).

Visuo-Spatial Working Memory

As described earlier, evidence for the storage of visual information has been available for many years. The use of visuo-spatial coding for verbal material was demonstrated particularly neatly by Brooks (1967), using a technique in which subjects were induced to store a sequence of sentences by recoding them in terms of a path through a visually presented matrix. Using this paradigm, Baddeley, Grant, Wight, and Thomson (1973) showed that visuo-spatial tracking, but not verbal coding, interfered with visual-imagery-based performance, in contrast to a broadly equivalent verbally coded task. Further work suggested that the coding was specifically *spatial* (Baddeley & Lieberman, 1980). However, using a somewhat different memory paradigm involving the use of visual imagery in paired-associate learning, Logie (1986) showed that performance could be disrupted by the simple requirement to observe patterns or patches of color, a *visual* rather than a spatial task.

Most disrupting tasks tend to involve both visual and spatial processing, and may also tend to have an executive component (see Logie, 1995, for a review). The technique recently developed by Quinn and McConnell (1996) appears to minimize disruption to anything other than the visual component of the working memory system. Their disrupting task simply requires the subject to fixate on a screen on which a large matrix of cells is continuously flickering on and off. They find that this influences performance when subjects are learning paired associates using an imagery mnemonic, while having no effect on rote learning performance, in contrast to the effects of irrelevant speech, which produces the opposite pattern.

Further evidence for separating visual and spatial aspects of STM come from the observation that pattern span, in which subjects have to reproduce a pattern of filled and unfilled cells in a matrix, is disrupted by the subsequent requirement to look at a series of abstract pictures, but not by a spatial tapping task, in contrast to the more spatial and serial Corsi Block Tapping Task, which shows exactly the opposite pattern (Della Sala et al., in press).

Neurobiological Evidence

Evidence for separate visual and spatial components of the STM system come from neuropsychological studies, with separate patients capable of performing the Corsi Block but not the pattern span task and vice versa (Della Sala et al., in press). Finally, neuroradiological evidence indicates the separability of visual and verbal memory (Smith, Jonides, & Koeppe, 1996), and within that, a distinction between spatial and object-based components (Smith et al., 1995). This area continues to develop, and further fractionation seems probable (Baddeley, 1998b).

Executive Processes

Individual Difference in Working Memory Span

While work utilizing the Baddeley and Hitch model has tended to concentrate on the slave systems, postponing a more detailed analysis of the central executive, North American research on working memory has tended to follow the opposite pattern, though with notable exceptions. Furthermore, while neuropsychological evidence has played a particularly important role in European research on working memory, North American research has been more strongly influenced by the psychometric tradition with its concern for individual differences within the normal population. The two approaches are complementary and will be considered in turn.

In a classic paper, Daneman and Carpenter (1980) operationally defined working memory as the system responsible for the simultaneous storage and manipulation of information. They developed a measure, *working memory span*, in which subjects were required to read out a series of sentences and then recall the final word of each. The maximum number of sentences for which all the final words can be correctly recalled is the working memory span, which for normal subjects ranges between 2 and 5. Daneman and Carpenter then demonstrated that span correlated highly with reading comprehension in a sample of student subjects. This finding has been replicated many times (see Daneman & Merikle, 1996, for a review). A series of follow-up studies contrasted subjects who were high and low in span, demonstrating, for example, that there were qualitative differences in the way in which prose is processed by the two groups; for example, high-span subjects are more able to resolve textual ambiguities and to carry information across from one sentence to another in order to do so (Daneman & Carpenter, 1983).

Views differ as to whether the measure was concerned with a language-specific system as proposed, for example, by Daneman and Tardif (1987) or reflects a more general executive processing capacity, as suggested by Turner and Engle (1989), who showed that a measure they call *operation span*, based on arithmetic, predicts reading comprehension virtually as well as the original sentence span.

Further support for the working memory span measure comes from Kyllonen and Christal (1990), who demonstrate that performance on a cluster of working memory span tasks correlates highly with more traditional measures of fluid intelligence while being less subject to the influence of prior knowledge and providing better prediction of success in acquiring practical skills such as programming than more traditional measures.

However, despite the apparent success of the working memory span measures, they have recently come under criticism, notably from Waters and Caplan (1996a, 1996b), who question the interpretation of earlier results and also report data from neuropsychological patients of various types that they claim are inconsistent with the theoretical interpretation offered by Carpenter and Just (1992). The criticism is relatively recent and the issue still unresolved (see Just, Carpenter, & Keller, 1996). It seems likely that working memory span probably involves the interaction of several cognitive subsystems. This highlights the importance of understanding the task if this approach is to continue to be fruitful.

Analysis of the WM span task has been one of the major problems tackled by Engle and his group. Engle (1996) showed that high-span subjects are better at generating items from semantic categories but, paradoxically, are more impaired than low-span subjects by the requirement to perform a concurrent task. This is interpreted as reflecting the successful use of attentional resources by the high-span subjects to minimize disruption from already generated items, a strategy that is disrupted by the concurrent load. Low-span subjects are unaffected by load because they are incapable or perhaps unwilling to use the inhibitory strategy, and are unaffected by a concurrent attentional demand. A similar intriguing pattern of results is obtained in studying performance on the Sternberg scanning task, for which there is again evidence for a qualitative difference in performance between high- and low-span subjects that is attributed to the capacity to maintain a memory representation against the disruption of potentially interfering items (Conway & Engle, 1994).

While Engle's work is highly creative in linking individual difference measures and more traditional memory measures such as category fluency and the Sternberg task, it appears to demonstrate qualitative differences in performance between high- and low-span subjects. These would seem to be at least as likely to result from differences in strategy as from a qualitative difference in the way in which the memory system works. In either case, the discontinuity casts doubt on using working memory span as a continuous measure. Even more seriously, these results suggest that many of the findings in this area, which are typically based on young students who are presumably of above-average intelligence for the population, may not generalize to samples of older subjects from a wider intellectual range. The success of Kyllonen in using the measures suggests that there is an important core to the work, but the measures are not yet well understood. At the very least, it would be useful to have work that separates out the role of the slave systems from that of executive processes. The necessity for such a separation is supported both by further psychometric research in the working memory span tradition (Shah & Miyake, 1996) and by the growing amount of evidence from functional imagery studies (Smith & Jonides, 1995).

Analysing the Central Executive

Work from a multicomponent approach to working memory has tended to use secondary task techniques, contrasting low processing load tasks such as articulatory suppression and spatial tapping that are targeted at the slave systems, with more demanding tasks, such as random generation of digits or key presses. Baddeley (1986) suggested that the capacity to produce a random stream of items such as digits or letters was constrained by the capacity of the central executive to break away from well-learned stereotypes such as the alphabet by continuously switching to new retrieval plans. Random generation does indeed dramatically impair complex tasks such as choosing the appropriate move in chess, in contrast to the simple suppression effect of reciting the alphabet (Robbins et al., 1996). Similarly, a concurrent digit span task can be shown to interfere with manual generation, with randomness decreasing linearly with digit load (Baddeley, Emslie, Kolodny, & Duncan, 1998).

The initial model of the central executive (Baddeley, 1986) was strongly influenced by Norman and Shallice's (1986) Supervisory Attentional System (SAS), and like the SAS was assumed to depend on the operation of the frontal lobes. However, a clear distinction was made between the question of anatomical localization and that of the functional analysis of the system assumed to reflect the operation of the central executive. It was suggested that the use of the term frontal syndrome should be avoided; the term *dysexecutive syndrome* was proposed as an alternative (Baddeley & Wilson, 1988).

One danger with the concept of a central executive is that of postulating a homunculus that is simply assumed to have whatever capacities are necessary to account for the data (Parkin, 1998). One response to this charge (Baddeley, 1998a) is to argue for the value of homunculi as a means of allowing the investigator to set aside some of the more intractable problems. The danger occurs when the theorist treats the homunculus as a solution rather than as a problem to be solved.

The question of how to analyze the central executive remains a difficult one. One approach is, of course, that based on individual differences described above. A second is to attempt to understand the breakdown of executive processes following brain damage in frontal lobe patients (e.g., Shallice & Burgess, 1996) or in patients suffering from Alzheimer's disease (Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991). Both these approaches have proposed a number of separable executive subprocesses, such as the capacity to focus and switch attention and to divide it among a number of sources. Division of attention appears to be particularly impaired in Alzheimer's disease, for example, while being relatively preserved in normal elderly subjects (Baddeley et al., 1991). Given the richness and complexity of executive processes, fractionation is likely to be a long and complex task. There is evidence to suggest, however, that it will benefit substantially from the development of functional imagery studies, which are already giving a very clear indication that different areas of the frontal lobes may be specialized for different executive functions (for an overview, see the papers included in Roberts, Robbins, & Weiskrantz, 1998).

Suppose that we are successful in identifying a finite array of executive processes, will we then have solved the central executive problem? Clearly not, since a crucial issue is the way in which the constituent processes interact. At present we have little evidence to constrain the possibilities, which range from a hierarchical structure with one dominant function, to an array of executive processes of approximately equal status, with a set of rules of interaction from which consensus emerges. If the former, then what is the process that dominates and, if the latter, what are the mechanisms that allow consensus to be reached? The same question arises within the more specialized subsidiary systems accessed. We know that verbal memory span is strongly influenced by phonological factors, but is in addition somewhat sensitive to visual similarity and can, of course, be strongly influenced by semantic and linguistic factors when sentences are retained. As a recent survey of current models of working memory illustrates (Miyake & Shah, 1999), the question of how information from different sources is integrated lies at the heart of many approaches to working memory and is likely to offer one of the most important and challenging problems facing the study of working memory in the years to come.

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