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EDITORIAL

Working memory[1]

INTRODUCTION

One approach to the problem of understanding human memory assumes that it is a modular system comprising functionally separate subsystems. Research within this framework attempts to identify the various memory subsystems by specifying their properties and functions, and seeks also to characterize interrelationships among them. An advantage of assuming modularity of function is that it provides a clear basis for relating hypotheses about normal memory and evidence from neuropsychological disorders of memory. Quite simply, such disorders are interpreted in terms of the level of functioning of the various subsystems. Certain 'pure' individual cases in which there is damage to a specific subsystem while others are intact may give strong support for distinguishing the subsystem in question and may also provide valuable clues as to its function. A fuller discussion of these issues is provided by Shallice (1979).

The recent history of the study of memory bears out the utility of a modular approach. Thus in the late 1960s the view that human memory can be characterized as a unitary system was superseded by the hypothesis that there are separate subsystems for sensory, short-term and long-term storage (see, for example, Baddeley, 1984). The principal impetus for this development was undoubtedly the mass of evidence concerning different patterns of performance in various laboratory tests of normal memory. However, neuropsychological evidence was also influential for distinguishing between the subsystems responsible for short- and long-term memory. Thus, on the one hand, patients suffering from classical amnesia could be characterized as having impaired long-term memory but intact short-term memory as measured, for example, by their normal digit span (Baddeley & Warrington, 1970). On the other hand, certain types of conduction aphasic patients were found with severely impaired digit spans but essentially normal long-term retention (Shallice & Warrington, 1970). Neuropsychological double dissociation of this sort is particularly powerful evidence for the separation of subsystems.

About 10 years ago short-term memory was typically assumed to be a unitary, limited capacity system for the temporary storage of verbal information over intervals of the order of a few seconds. Such information could be refreshed or transformed by active control processes like subvocal rehearsal, provided that the capacity of the system was not exceeded. This capacity was widely thought to be reflected in the typical memory span of about 7, the maximum number of random verbal items that can be recalled in the correct sequence immediately after presentation. The short-term memory system was also assumed to function as a 'working memory' in a range of activities requiring temporary information storage, such as problem-solving and speech comprehension. However, a feature of much research on short-term memory was that it tended to concentrate on tasks involving the storage of strings of digits, letters or words while ignoring broader questions about its function as a working memory in normal cognition. Furthermore, results obtained in apparently minor variants of these standard tasks were becoming increasingly complicated, making it more and more difficult to maintain a coherent view of a unitary short-term store. Alan Baddeley and I therefore proceeded to investigate the question of working memory by studying the function of short-term storage in information processing, to try to break out from what appeared to be fast becoming a somewhat sterile theoretical impasse (Baddeley & Hitch, 1974).

One of the techniques we adopted was to study the effects of loading a person with the task of temporarily remembering irrelevant digits while simultaneously engaging in an activity such as verbal

[1] Address for correspondence: Dr Graham J. Hitch, Department of Psychology, University of Manchester, Manchester M13 9PL.

reasoning, comprehending a prose passage or learning a list of words. If the digits occupy a common working memory they should lead to interference, especially when the load is close to the capacity of the system, i.e. near to digit span. The results showed a consistent pattern of interference across activities: small additional digit loads did not lead to measurable interference while near-span loads did. However, the amount of interference from near-span loads was relatively small, and was certainly far less than would be expected on the assumption of a unitary working memory system serving a crucial central role. To account for this and certain other aspects of our results we proposed the concept of a modular working memory system, with different tasks loading the components of the system differentially. Working memory was seen as a set of limited-capacity subsystems comprising a 'central executive' attentional system controlling slave subsystems which specialize in different types of temporary storage. The latter included a speech-based 'articulatory loop' associated with subvocal rehearsal and a visuo-spatial subsystem involved in imagery, subsequently referred to as the 'visuo-spatial scratch-pad' (Baddeley & Lieberman, 1980). There are various accounts of the detailed nature of this system and its role in such activities as reading and mental arithmetic (Baddeley, 1979; Hitch, 1978). The present article focuses on the nature of the slave subsystems for verbal and visual short-term storage and uses these examples to try to illustrate the complementarity which exists between neuropsychological data and studies of normal function. It is also suggested that studies of developmental aspects of memory have been somewhat overlooked and may have a useful part to play in the contribution to our general understanding.

ARTICULATORY LOOP

It has been known for some time that immediate memory for a sequence of letters or words is impaired when the items sound alike (Baddeley, 1966; Conrad & Hull, 1964). Performance in this situation is also sensitive to word length, with words of longer spoken durations being less well recalled (Baddeley *et al.* 1975). Both these effects disappear when the subject is required to articulate irrelevant words such as 'the–the–the' during the memory task (Murray, 1968; Baddeley *et al.* 1975). These converging effects of phonemic similarity, word length and articulatory suppression suggested the concept of a speech-based store associated with subvocal rehearsal, the 'articulatory loop'. The capacity of the loop appears to be time-based rather than item-based, since studies of the word-length effect show that people can recall as many items as they can articulate in from 1 to 2 seconds (Baddeley *et al.* 1975). One interpretation of this relationship is that traces in the loop decay in 1–2 s unless refreshed by subvocal rehearsal; thus fewer long words can be maintained because they take longer to rehearse.

There are problems for any simple interpretation of the articulatory loop, however, since the effects of articulatory suppression are only straightforward in the manner described when materials are presented visually. For auditory materials articulatory suppression removes the effect of word length on recall but not that of phonemic similarity (Baddeley, Lewis & Vallar, personal communication). Some light has been shed on this asymmetry between presentation modalities by studies of the disrupting effects of hearing irrelevant speech while encoding visually presented materials for immediate recall (Salame & Baddeley, 1982). Irrelevant speech is more disruptive when it is phonemically similar to the items being remembered, but hearing long words causes no more interference than hearing short ones. Salame & Baddeley took this as suggesting that the irrelevant speech is not itself articulated (the process responsible for word-length effects), but does gain access to a phonological store (the locus of phonemic similarity effects). They therefore proposed a subdivision of the articulatory loop into two components, maintaining that articulatory suppression disrupts subvocal rehearsal but not the passive phonological store. They also assumed that auditory materials enter the phonological store directly through obligatory analyses of the speech input, while visual materials have first to be subvocalized. These assumptions are sufficient to account for the dependence of articulatory suppression effects on presentation modality. They also account for the further finding that the disruptive effect of hearing irrelevant speech is removed when the subject is engaged in articulatory suppression. In functional terms it is suggested that the phonological store is linked to the perception and comprehension of speech. The articulatory control process is, of course, clearly associated with mechanisms for speech production.

The idea that there are separate components of the articulatory loop raises the possibility of different patterns of neuropsychological impairment of verbal short-term memory. For example, there are now well-documented cases of conduction aphasia where poor span has been observed in association with normal spontaneous speech and fluent articulation (Shallice & Butterworth, 1977; Vallar & Baddeley, 1984). Nevertheless, the patients had deficits in speech comprehension as measured by the longer sentences in the Token Test (de Renzi & Vignolo, 1962), suggesting a deficit to the speech input store with intact mechanisms for subvocalization. Vallar & Baddeley (1984) investigated their patient in some depth and showed that her auditory span of 2–3 items was reduced for phonemically similar materials but unaffected by word length. This is consistent with the use of a phonological store of reduced capacity, but suggests also that the patient was not using subvocal rehearsal, despite her ability to articulate normally. The absence of subvocal rehearsal was also suggested by the insensitivity of her visual span of about 4 items to phonemic similarity or word length. Vallar & Baddeley suggested that the patient would gain little from using subvocal rehearsal when the phonological store is impaired. This seems a reasonable supposition, but it is a reminder that separate components within subsystems are not completely independent.

Despite the lack of full independence, it should be possible to find selective impairment of the articulatory control process but normal phonological storage. The obvious patients to investigate here are cases with a pronounced and specific impairment of speech articulation. Nebes (1975) reported an anarthric stroke patient who had an auditory digit span of 6 and normal comprehension as assessed by the Token Test. Vallar (personal communication) reported another patient like this and, in addition, showed that his auditory span was sensitive to phonemic similarity of the materials but insensitive to word length. The latter points directly to an absence of subvocal rehearsal. These patients' normal speech comprehension and near-normal auditory span, however, is in contrast to the pattern in the conduction aphasics described earlier and suggests an intact phonological input store.

Thus the neuropsychological evidence can be interpreted in terms of a distinction between components of the articulatory loop based on data from normal subjects. There are, however, a number of problems for the current theoretical analysis. One of these is the assumption that entry of visual materials into the phonological store depends on the process of articulation. For example, despite being anarthric the patients studied by Nebes and Vallar could make accurate rhyme judgements when presented with printed words. Furthermore, the ability of normal individuals to make such judgements is largely unimpaired by concurrent articulatory suppression (Baddeley & Lewis, 1981; Besner *et al.* 1981). These results are not inconsistent with the idea of a non-articulatory phonological system, but they challenge the idea that visual inputs have to be articulated in order to access the system. A second problem is the recent argument that irrelevant speech disrupts memory by competing for articulatory processes rather than by interfering with a phonological store (Broadbent, 1984). The basis for this view is that interference depends on irrelevant speech being simultaneous with the memory task. On the other hand, there is evidence that word length of the irrelevant speech is unimportant, suggesting that the speech itself is not rehearsed. Debate on this issue is likely to continue. More generally, Broadbent (1984) argues that there are separate stores for speech input and speech production: this differs from the formulation described here in which these two functions are more intimately connected as aspects of a single subsystem. A third and related question is whether the temporary storage involved in speech perception is purely phonological, since there is evidence to suggest the existence of a system sensitive to higher-level syntactic variables (Hitch, 1980). However, while all these problems represent important issues, they do not detract from the considerable success of the present, albeit simple, concept of the articulatory loop in accounting for many detailed aspects of normal and abnormal short-term memory.

VISUO-SPATIAL SCRATCH-PAD

It is widely accepted that we can construct visual images in the absence of direct sensory stimulation. In a well-known series of studies, Brooks (1967, 1968) demonstrated that tasks which involve imagining spatial relations over short intervals are disrupted by concurrent visual perceptual processing, whereas formally equivalent verbal tasks are interfered with most by concurrent verbal processing. This suggests that there may be a separate system specializing in dealing with visuo-spatial information. Subsequent research has shown that the type of imagery studied by Brooks can be disrupted by the concurrent non-visual but spatial task of tracking the path of a moving sound source. However, it is largely unaffected by the concurrent visual, non-spatial task of detecting changes in the brightness of a large patch of light (Baddeley & Lieberman, 1980). Further evidence shows that making actively-controlled eye movements interferes with the ability to perform this sort of imagery, but that equivalent changes in visual input while the eyes remain stationary have little effect (Baddeley, 1983). Baddeley has proposed the idea of a specialized subsystem for imagery referred to as the 'visuo-spatial scratch-pad' to account for these findings. It is suggested that the system can be used to maintain spatial relations using some covert analogue of eye movements, in a similar fashion to the use of subvocalization in the articulatory loop.

At present, this concept is considerably less well understood than the articulatory loop. One problem is that there are a number of techniques for exploring visuo-spatial short-term memory and it is not yet clear that they converge to a common underlying mechanism. One such technique involves showing subjects two letters separated by a brief delay and asking whether they are the same (Posner & Keele, 1967). Visually identical pairs (e.g. AA) receive faster responses than non-identical pairs (aA) at short delays, suggesting the persistence of some form of visual representation for up to a few seconds. Subsequent research has distinguished this form of visual memory from sensory (iconic) storage, but its precise characteristics remain somewhat unclear. Two factors which complicate the interpretation of the letter-matching task are the possible role of verbal coding of the alphabetic stimuli, and the existence of well-learned representations in long-term memory. A technique which avoids both problems involves short-term memory for matrices with randomly filled cells. These are novel patterns which cannot easily be given verbal descriptions (Phillips, 1984). Subjects are typically presented with a series of such patterns and their memory is tested either immediately or after a short delay. On immediate test the final pattern is remembered particularly well, while the retention of earlier patterns is at a uniformly lower level (Phillips & Christie, 1977). Phillips interpreted this single-item recency effect in terms of a process of active visualization of the final pattern. Visualization is distinguished from the longer-term retention of earlier patterns because it is disrupted by post-list activity and is unaffected by changing the presentation rate, whereas memory for earlier patterns is unaffected by post-list activity but is sensitive to the presentation rate (Phillips & Christie, 1977). Like Posner's visual code, visualization is not simply sensory memory since it is not sensitive to masking by further visual stimulation. Subsequent research has shown that visualization can be maintained for several seconds, provided that there is no distraction; however, when there is distraction, tasks which also involve visualization are more disruptive than equivalent tasks requiring phonemic categorization (Phillips, 1984). Thus results obtained with this technique lend fairly clear support for the idea of a specifically short-term component of visual memory. However, as stated previously, it is at present uncertain whether this system should be thought of as being equivalent to the visuo-spatial scratch-pad investigated by Baddeley. One possible difference is that evidence for the scratch-pad is based on memory involving spatial relations, while Phillips' technique appears to focus on memory for visual pattern information. There may be functional differences between the maintenance of these conceptually distinguishable types of visuo-spatial information.

Neuropsychological research tends to support a distinction between visuo-spatial and verbal components of working memory. For example, conduction aphasic patients of the type discussed earlier with markedly impaired auditory digit spans typically show rather higher spans when material is presented visually (see Warrington & Shallice, 1972). In view of the deficient phonological storage in these patients, these findings are obviously suggestive of a separate system for visuo-spatial storage. Indeed, in one such case Warrington & Shallice (1972) were able to demonstrate that the patient had a tendency to make visual confusion errors in immediate recall, as would be expected on this view. More direct evidence comes from studies of specific impairment to visuo-spatial short-term memory. De Renzi & Nichelli (1975) compared the performance of various groups of brain-damaged patients on both auditory digit span and the Corsi test of spatial memory span. In the Corsi test the patient views the examiner tapping a subset of a random arrangement of wooden blocks and then immediately tries to tap out the sequence. Spatial span is assessed by gradually increasing the sequence length until the subject makes errors, normal performance being limited to 5 or 6 blocks. De Renzi & Nichelli found a convincing dissociation between digit span and block span, with the spatial task being sensitive to posterior lesions in either hemisphere and auditory digit span being impaired by damage to the left hemisphere. They were also able to identify single cases which illustrate the dissociation particularly clearly. One conduction aphasic patient had a very low digit span of about 3 items, while her spatial span was essentially normal; conversely, two patients with right posterior lesions scored normally on digit span, yet had block spans of only 2–3 locations.

Although this neuropsychological evidence provides reasonably strong support for a dissociation between verbal and visuo-spatial components of working memory, it is unfortunately not clear that the visuo-spatial component can be identified with either the scratch-pad concept or Phillips' visual short-term memory. Since the Corsi test clearly has a high spatial-motor component, it probably has more in common with the spatial imagery tasks studied by Brooks and by Baddeley than the visual pattern memory studied by Phillips. A recent neuropsychological study by Haxby *et al.* (1983) hints at a distinction between these two aspects of visuo-spatial short-term memory, since Korsakoff amnesics were observed to have impaired immediate recognition memory for visual abstract drawings but essentially normal Corsi spans. Further research is necessary to confirm this apparent dissociation and to investigate whether it corresponds to a spatial/figural distinction or a difference between motoric and non-motoric coding. Thus, within the working memory framework, it seems clear that the concept of the scratch-pad will have to be modified and elaborated, just as the idea of the articulatory loop is undergoing revision. In both cases neuropsychological evidence is clearly highly relevant and is likely to continue to play an important role in the advance of our understanding.

DEVELOPMENTAL CHANGES IN WORKING MEMORY

It has been suggested that the study of short-term memory abilities in children can contribute to our understanding of memory in much the same way that neuropsychological evidence has proved useful (Hitch & Halliday, 1984). Thus, if functionally independent memory subsystems follow separate patterns of developmental change, developmental differences in memory performance ought to be consistent with hypotheses about the nature and identity of these subsystems. The first step in such an approach is to establish that some of the methods and concepts derived from studying working memory as a modular system in adults are applicable to children. If this can be established, developmental investigations offer an opportunity to test hypotheses about the nature of specific subsystems and may also provide a valuable source of fresh ideas.

Recent work on the developmental increase in the size of verbal memory span illustrates the applicability of a modular approach. It will be recalled that studies of the effect of word length on immediate memory in adults suggested that the articulatory loop has a time-based capacity such that people can remember as many items as they can rehearse subvocally in between 1 and 2 seconds. Nicolson (1981) used the word-length effect to investigate developmental changes in immediate memory in children aged between 8 and 11, measuring in addition the rate at which children could articulate the materials. There was a steady developmental improvement in the fluency of articulation which, assuming a constant temporal capacity for the articulatory loop, was sufficient to account for both the general improvement in memory with age and the size of the word-length effect within different age-groups. From this analysis it appears that the developmental growth in verbal immediate memory from 8 upwards does not reflect an increase in the capacity of an underlying store, and is due instead to improvements in the efficiency of the control process of subvocal rehearsal in the articulatory loop.

Further research in our own laboratory has confirmed Nicolson's findings and has shown that the results extend to younger children aged 5 or 6, provided that materials are presented auditorily. If materials are presented as nameable pictures, however, such young children's memory is not affected by the word length of the picture names (Hitch & Halliday, 1984). This is an interesting difference, since in older children and adults both methods of presentation give rise to similar word-length effects. Subsequent investigations have further explored developmental change in memory for pictures. It emerges that older children's memory is impaired by phonemic similarity of the picture names and that both this and the word-length effect are markedly reduced by articulatory suppression (Hitch & Halliday, 1984; Halliday *et al.* 1983). In younger children, however, effects of phonemic similarity and articulatory suppression are not observed, in keeping with the absence of an effect of word length. Thus there appears to be a qualitative change in span for pictures such that 5–6 year olds do not use the articulatory loop, but there is a smooth development in span for auditory materials with use of the loop at all ages studied. This contrast may be related to the suggestion that auditory materials receive obligatory phonological processing, while entry of visual materials into the loop is via the optional control process of articulation. It raises the question of the type of storage used by young children to retain the 2–3 pictures that they can typically recall. Some investigators have reported that such young children's memory for visual materials is impaired by visual similarity (Conrad, 1972; Hayes & Schulze, 1977), suggesting that visuo-spatial short-term storage can be implicated. If so, there may be interesting comparisons to be made between short-term retention in early childhood and the patterns of breakdown observed in some types of brain-damaged adults. Thus there is perhaps sufficient evidence from work with children to suggest that such investigations may provide a fruitful additional line of enquiry which can complement studies of normal and abnormal function in adults.

CONCLUSION

This article has not attempted a systematic review of the literature on working memory and, in particular, it has not discussed such important issues as the nature of the central executive subsystem or the role of working memory subsystems in activities like reading or mental arithmetic. By concentrating on the articulatory loop and visuo-spatial scratch-pad, an attempt has been made to illustrate the close relationships that exist beween studies of normal function and the investigation of certain types of neuropsychological disorder, and the possible further contribution that can be made by developmental studies. It has been argued that an approach which assumes that human memory has a modular structure facilitates the integration of evidence from such different sources. It seems likely that the verbal and visuo-spatial components of working memory will continue to be explored along these lines and, it is to be hoped, that a clearer specification of their structure and function will eventually emerge.

GRAHAM J. HITCH

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