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Memory updating in working memory: The role of the central executive

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Two experiments are reported which suggest that a dynamic memory updating task, running memory, requires two independent mechanisms – the articulatory loop and a component of the central executive. Experiment 1 shows that irrelevant speech and articulatory suppression impair the serial recall component of the running memory task but not the updating component. Updating memory affects performance independently of the effects of irrelevant speech and suppression. The second experiment produced the same pattern of results with a close to span memory load. These results are interpreted in terms of the working memory model outlined by Baddeley (1986). It is concluded that the updating of working memory in real time is coordinated by a central executive component of the model.

The working memory model proposed by Baddeley & Hitch (1974) consists of three components: an *articulatory loop*, holding speechlike representations, a *visuo-spatial scratch pad*, holding imaginal representations and a *central executive*, which acts as an overseer directing attention and coordinating the activities of the other components.

A considerable body of work has been generated on the articulatory loop and the visuo-spatial scratch pad, but the central executive has tended to remain an area of residual ignorance within the working memory model (Baddeley, 1981). This is not perhaps surprising given that the executive is likely to be a very complex entity. However, Baddeley (1981) has also suggested that this component may be fractionable, i.e. we may be able to 'chip off' independent functional components.

The most recent formulation of working memory (Baddeley, 1986) incorporates a model of attentional control proposed by Norman & Shallice (1986) in an attempt to understand the nature of the central executive. In this model most cognitive processing is initiated by existing schemata which are activated automatically by in-built priorities and environmental cues. A similar 'production system' approach (Newell & Simon, 1972) was also proposed by Broadbent (1984) as the coordinator in his 'Maltese Cross' model of memory. In the Norman & Shallice formulation an additional mechanism, the supervisory attentional system (SAS), was also proposed. This roughly corresponds to the central executive of working memory and 'operates entirely through the application of extra activation and inhibition to schemas in order to bias their selection by the contention-scheduling mechanisms' (Norman &

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Shallice, 1986, p. 6). Such contention-scheduling mechanisms are responsible for resolving competition and facilitating cooperation between structures by using the activation values of schemata as the sole selection criteria. Norman & Shallice suggest that the SAS is required to perform tasks that are novel, involve planning, decision making or trouble shooting, or are generally difficult or perceived as dangerous. Such activities require a working memory system that is both dynamic and flexible in its capabilities, and this was one major attraction of the working memory formulation over the simpler modal model (Baddeley, 1981).

Unfortunately, it can be technically quite difficult to design experiments that tap central executive functions because one would expect the system generally to operate as a highly integrated system. Thus, it is resistant to fractionation using dual-task paradigms. However, the role of the central executive in controlling the encoding operations of the visuo-spatial scratch pad was examined by Morris (1987) and he concluded that executive control was required at encoding but *not* during maintenance rehearsal, because secondary tasks that placed a load on the central executive only produced performance decrements during encoding. This does indeed imply that the working memory system acts as an integrated system during active processing, and that the system will 'resist' fractionation during these phases because the demand characteristics of the task require this 'cohesion'. If this is the case, then one strategy for examining the role of the executive is to interfere with the operation of the 'slave systems' during these dynamic phases of processing while at the same time placing a heavy load on the executive and observing the degree of interference.

Such an approach requires the use of dynamic memory tasks to tap the dynamic aspects of memory processing. The load on the executive can then be manipulated by varying this 'dynamism' or the real-time processing demands of the task. One activity that provides such demand characteristics is memory updating. This phenomenon has been investigated by Bjork (Bjork, 1978; Bjork & Landauer, 1978). Earlier research on this largely neglected topic is reported in Yntema (1963) and Yntema & Mueser (1960, 1962). Memory updating is the act of modifying the current status of a representation of schema in memory to accommodate new input. An everyday example of this would be the modification of the entry for a person's current telephone number. When the number is changed it is the new number, not some earlier number, that must be retrieved from memory. Similarly, as Bjork points out, it is tactful to remember the name of a friend's current spouse rather than the partner prior to divorce. Bjork (1978) showed that such updates in long-term memory are not destructive, so that earlier updates can usually be recalled although there is a distinct recency effect (Baddeley & Hitch, 1977). It might be argued that updating long-term memory is not a particularly dynamic process because the time elapsing between updates suggests a discontinuous process and thus such observations are largely irrelevant to working memory. However, Bellezza (1982) has shown that the method of loci mnemonic can be used to rapidly update memory and such imagery mnemonics can be held in spatial working memory during encoding and retrieval (Baddeley & Lieberman, 1980; Logie, 1986). Other tasks with an obvious updating component, for example counting (Logie & Baddeley, 1987) and mental arithmetic (Hitch, 1978), also require working memory resources.

Thus there are a number of tasks that require memory updating. However, such tasks do not provide an easily quantifiable memory load. Furthermore, it is desirable to use a primary task that is comparatively well understood and susceptible to disruption from sources of interference that are also well understood. Within the working memory framework the articulatory loop is the component of the system that has been mapped out in most detail (Baddeley, 1986). It is known, from a number of diverse paradigms, for example, that it has a temporal capacity of about 1.5–2 seconds (Baddeley, Thomson & Buchanan, 1975; Ellis & Hennelley, 1980; Morris & Jones, 1987) and there are two relatively well-understood sources of interference – articulatory suppression (Baddeley, Lewis & Vallar, 1984) and unattended speech (Salame & Baddeley, 1982, 1989; Jones, Miles & Page, in press) – that disrupt the operation of the loop. If neither of these secondary tasks impairs executive functioning, then the effects of variable executive load should be independent of the effects of disrupting the performance of the articulatory loop.

A major problem in studying the role of the central executive is finding a task that has *distinct* components that require the capacity of the central executive and the articulatory loop. The classic task for examining the articulatory loop is serial recall of strings of digits or consonants. Both articulatory suppression and exposure to unattended (or more accurately irrelevant) speech are known to disrupt this process. However, this task is unlikely to place a heavy burden on executive resources given that a number of studies have shown that holding such a verbal load in working memory does not *seriously* disrupt other cognitive processes such as verbal reasoning (Hitch & Baddeley, 1976) and spatial processing (Morris, 1987). This supports the contention of Baddeley (1986) that a major role of the executive is to coordinate cognitive processes and their execution rather than to provide a memory substrate. If this is the case, the executive is involved in the dynamic aspects of real-time processing in working memory and not the passive maintenance of memory loads.

To examine this proposition a task that requires both dynamic processing and the resources of the articulatory loop is required. One task that meets these requirements is running memory, a paradigm that was first used by Pollack, Johnson & Knaft (1959) (see also Pollack & Johnson, 1963; Waugh, 1960). This task requires subjects to listen to, or watch, strings of items of unknown length from the subject's perspective, and then serially to recall as many items as possible or a specific number of recent items. In the latter case a subject may, for example, be presented with lists of 6, 8, 10 and 12 items and be required to recall the six most recent items. This means that subjects must hold, in memory, the first six items presented and then, if there are more than six items in a list, they must update the contents of memory by dropping the 'oldest' item and adding the most recent to the string. This updating process must be repeated for each supra-span additional item. Such a procedure requires subjects to make 0 to N updates with subsequent serial recall.

If memory updating requires central executive resources but not the articulatory loop, and the serial recall aspect of the task requires the articulatory loop but not the central executive, then the number of updates and the effects of secondary tasks that are known to disrupt the articulatory loop should not interact. An interaction of updating with secondary tasks would imply that a larger memory set placed a greater load on memory and thus made performance more sensitive to the interference tasks. However, there should be main effects of both number of updates, because it is postulated that this activity requires the central executive rapidly to revise the set of items to be held in working memory, and of secondary task, because the serial recall component of the task requires the resources of the articulatory loop.

This article describes two experiments which examined the effects of articulatory suppression and irrelevant speech on running memory when subjects must serially recall the last four items presented (Expt 1) and the last six items presented (Expt 2). The predictions were that there would be main effects of both number of updates and secondary task but no interaction of the two. The first experiment examined the effect of updating when N is below the memory span of most subjects. Experiment 2 was included to examine the effect of a memory load that is close to, or beyond, the span of subjects and to replicate and extend the range of the findings from the first experiment.

Experiment 1

Method

Subjects. Eight female and four male undergraduates, with a mean age of 20, volunteered to participate in this experiment. They were paid £3.00 for a session lasting one hour.

Materials. A total of 56 lists of consonants were randomly generated. No consonant appeared twice in the same list and any obviously meaningful acronyms were deleted. These were split into four blocks of trials. The first eight trials were used for demonstration and practice and the remainder were split into three blocks of 16 trials. Within each block there was an equal number of trials of each list length. The list lengths were four, six, eight and ten items. These lists were then entered into a computer database.

A tape was also recorded. This consisted of a five-minute passage of *Don Giovanni spoken* in Italian, an irrelevant speech source used by Morris, Jones & Quayle (1989) to disrupt serial recall of visually presented consonants. The five-minute passage was edited onto a tape four times to produce a continuous recording lasting 20 minutes. This was subsequently presented to subjects through headphones at an average level of 65 dB (A).

Response sheets were prepared with separate boxes each made up of four boxes for each string. However, there was no indication of the list length associated with each string.

Procedure. Within a block of trials, the ordering of list length was randomized with the constraint that not more than two lists of the same length should be presented consecutively.

There were three treatments and four conditions in the experiment. In the irrelevant speech treatment, speech was presented through headphones. Subjects first experienced this in the practice phase of the experiment and were told to ignore it as best they could throughout the session. In the articulatory suppression treatment subjects wore headphones but heard nothing through them. They were told that they should whisper the word 'the' at a rate of about twice per second throughout this block, including the recall periods. In the quiet treatment headphones were worn and no articulatory suppression was required. This experiment used a completely balanced design with ordering of both blocks and treatments assigned using a Latin square. Subjects experienced all treatments during practice.

The consonants were presented in the central location of a video-monitor at a rate of one per second and subjects instigated a trial by pressing the space bar on a BBC Model B microcomputer. A tone, clearly audible when accompanied by irrelevant speech, was presented half a second before, and half a second after, the presentation of each list. Strict forward serial recall was required, i.e. subjects were required to recall serial position 1 before 2 etc., and they were required to guess any item they could not remember before making the next response.

The experimenter explained to each subject that the length of a given list might be four, six, eight or 10 items long and that the ordering of these lists was random. They were also told that they should only recall the last four items presented. It was stressed that some lists would be only four items long so they could not afford to ignore any items. They were not told how many trials of each length would be presented. The experiment had a completely within-subject design and the experimenter was present throughout.

Results

The responses for each condition (number of updates) and treatments (quiet, articulatory suppression and irrelevant speech) were scored as number correct for each serial position (maximum of four for each serial position) and these are plotted in Fig. 1. The notation used for conditions is 0 (no updates; four items presented), +2 (two updates required; six items presented), +4 (four updates required; eight items presented) and +6 (six updates required; 10 items presented).

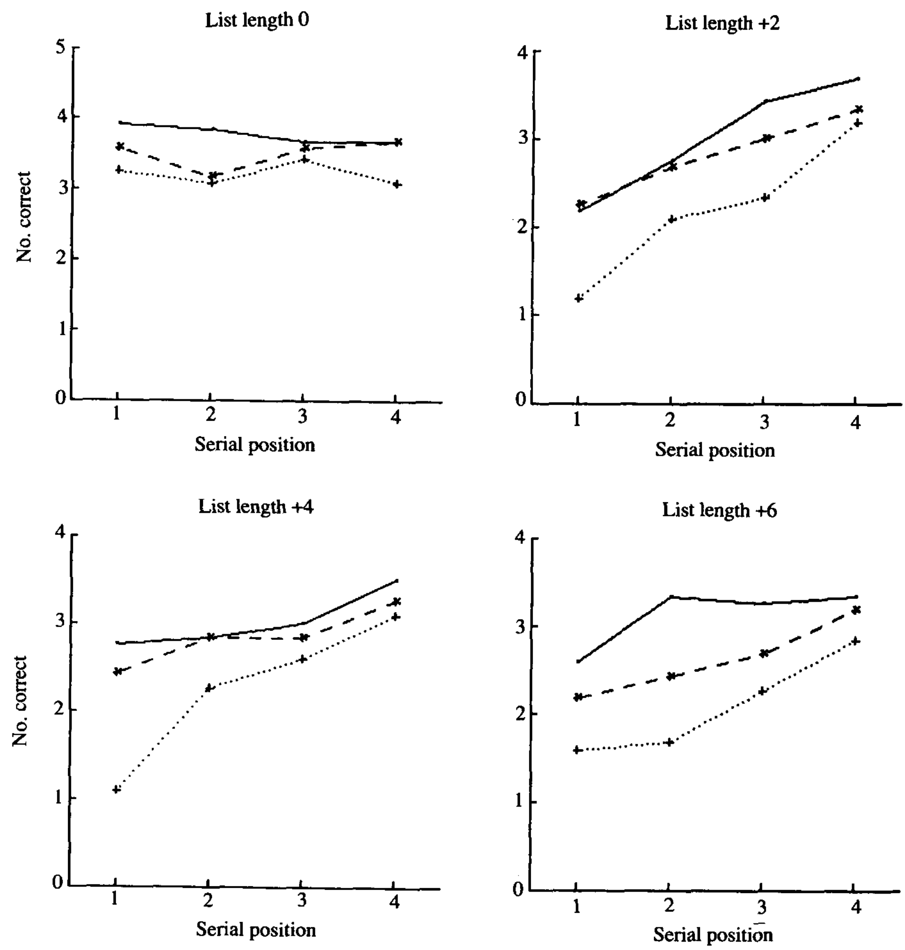

Figure 1. Mean number of items correctly recalled (max. = 4) with a memory load of four items and 0, 2, 4 and 6 memory updates. ·——·, quiet treatment; + · · · · · · +, with articulatory suppression; × — — ×, with irrelevant speech.

A three-way repeated measures design analysis of variance with four conditions, three treatments and four serial positions was performed on the data. There were main effects of condition ($F(3, 33) = 16.90$, $p < .00001$), treatment ($F(2,22) = 33.05$, $p < .00001$) and serial position ($F(3,33) = 19.42$, $p < .00001$). As predicted, conditions and treatments did not interact ($F(6,66) < 1$) but both conditions ($F(9,99) = 4.09$, $p < .001$) and treatments ($F(6,66) = 3.73$, $p < .01$) interacted with serial position. The higher order interaction was not significant ($F(18,198) < 1$).

Simple main effects analysis was used to examine the interactions (Kirk, 1968). This analysis showed treatment effects at all serial positions (serial positions 1–3, $p < .001$, position 4, $p < .01$) and serial position effects for each treatment (all comparisons $p < .001$). Further analysis using the Newman–Keuls procedure showed significant disruption by articulatory suppression at each serial position (all comparisons $p < .001$) and effects of irrelevant speech at positions 1–3 (5, 1 and 5 per cent, respectively). There was no significant effect of irrelevant speech at position 4 and articulatory suppression was significantly more disruptive than irrelevant speech at all serial positions (all comparisons, $p < .01$). Thus, both articulatory suppression and irrelevant speech disrupted performance of the serial recall component of the task independently of the number of updates that had to be made.

Further simple main effects analysis showed that condition disrupted performance at all serial positions except position 4 (all other comparisons, $p < .01$). Newman–Keuls comparisons on positions 1–3 showed significant decrements at all positions by +2, +4 and +6 updates compared with zero updates (all comparisons, $p < .01$). However, all comparisons amongst non-zero updates were non-significant. This indicates that memory updating *per se* is seriously disruptive but this is independent of the number of updates that must be made.

Discussion

These results therefore show that both treatments and conditions disrupt running memory performance independently. Postulating a null hypothesis is of course problematic because of the possibility of making a Type II error. However, as the F ratio for the condition × treatment interaction was less than unity, the possibility that a Type II error can account for this finding is remote. An interesting finding that was not predicted is that, although the act of updating is disruptive, the *number* of updates does not seem to be important. This suggests that updates themselves are independent as the updating operations did not have a cumulative effect on executive resources, at least within the confines of this experiment. The second experiment explored this further by replicating the first study with a memory load that was close to memory span. In the first experiment subjects may have simply held more than four items in working memory rather than updating the subset of items for lists $> N$. This explanation is not very plausible because (*a*) memory span would be reduced in the presence of interference and (*b*) updating would still be required when the longest list lengths were presented. However, if the central executive is used to *hold* items rather than simply being required to *control* memory resources then performance with longer list lengths should interact with treatments, because in this situation the subject's verbal memory resources should be seriously burdened.

Experiment 2

Method

Subjects. Six male and six female subjects from the same pool volunteered for this experiment. None of these subjects participated in Expt 1.

Materials and procedure. All materials and the procedure were identical to those of Expt 1 except that the list lengths were extended and subjects had to recall the last six items. Condition 0 therefore used a list length of six, +2 used eight items, +4 used 10 items and +6 used 12 items.

Results

The mean number correct for each condition and treatment is plotted in Fig. 2 and an analysis of variance identical in design to that used for Expt 1 was performed on the data. Once again there were main effects of condition ($F(3,33) = 7.50, p < .001$), treatment ($F(2,22) = 24.97, p < .001$) and serial position ($F(5,55) = 44.19, p < .0001$) and the predicted lack of interaction between condition and treatment was supported ($F(6,66) < 1$). Treatment interacted with serial position ($F(10,110) = 3.59$, $p < .001$) but condition did not ($F(15,165) < 1$) and there was no higher order interaction ($F(30,330) < 1$). Thus this experiment produced the same pattern of results as Expt 1 except that an interaction between condition and serial position was not found.

Simple main effects analysis showed effects of treatment at all serial positions except position 6 (all other comparisons, $p < .01$) and serial position effects were found for each treatment (all comparisons, $p < .01$). Newman–Keuls comparisons of articulatory suppression with quiet treatment revealed deficits at positions 1–5 (all comparisons, $p < .01$) but the effects of irrelevant speech were confined to positions 1–3 (1, 5 and 1 per cent, respectively). Performance with articulatory suppression was worse than with irrelevant speech at serial positions 1–4 (5 per cent for position 1, 1 per cent for positions 2–4). Thus, once again the interference tasks seriously impaired the performance of the articulatory loop.

Further analysis of condition using Newman–Keuls comparisons revealed that all updates impaired performance (+2, $p < .01$, +4, $p < .05$ and +6, $p < .01$) but once again all other comparisons were non-significant. Thus the pattern of results in this experiment is virtually the same as in the first experiment.

General discussion

The patterns of results from the two studies are broadly similar and show that memory updating is not performed by the articulatory loop, and that such updating is also independent of the memory load (at least within the range explored in these studies). Another interesting, and counter-intuitive, finding is that the number of updates that must be made does not affect performance. This implies that the executive can either perform several updates in rapid sequence without overloading its capacity or it has a very rapid 'recovery' rate when performing such operations. The latter feature would be an important capability for a real-time processor.

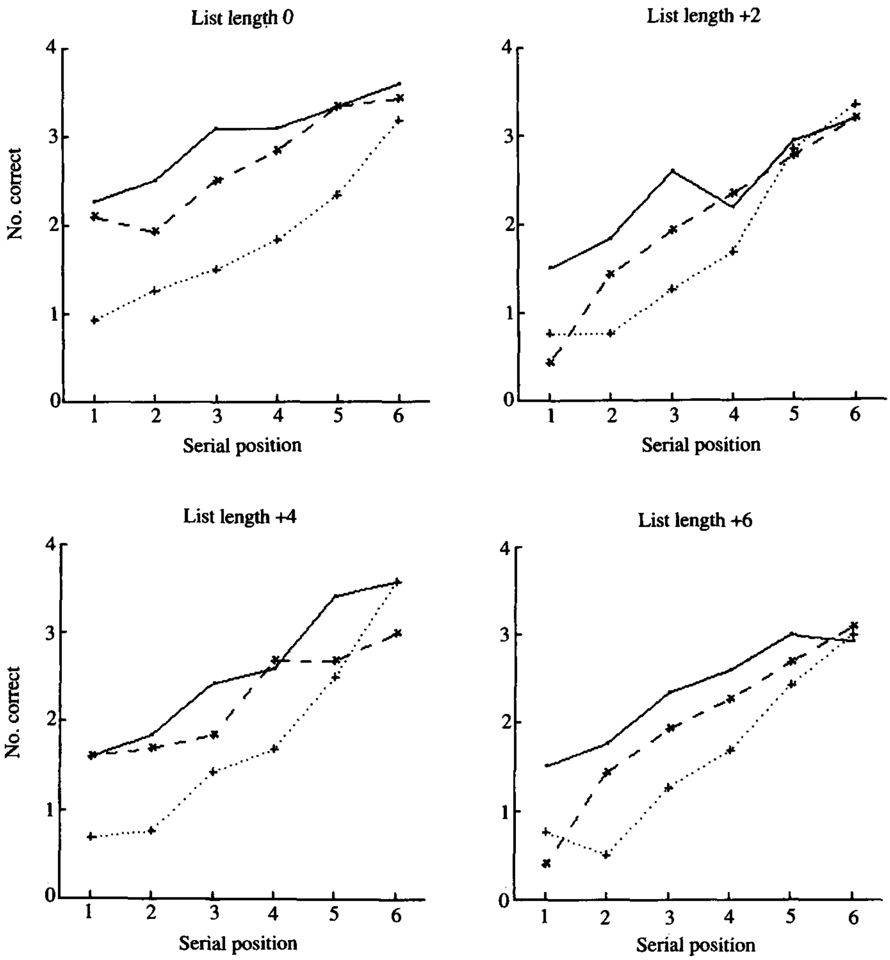

Figure 2. Mean number of items correctly recalled (max. = 4) with a memory load of six items and 0, 2, 4 and 6 memory updates. ·——·, quiet treatment; + · · · · · · +, with articulatory suppression; × — — ×, with irrelevant speech.

One way in which updating might be achieved would be to rely on passive storage. Passive storage has been suggested as a means of accounting for recency effects in working memory (Baddeley, 1986). From this perspective the most recent items overwrite earlier items and the appropriate set of items is simply rehearsed by subvocal articulation. Thus, unrehearsed items are 'erased' as they are replaced. Indeed, Baddeley has commented that 'the system is being constantly updated and modified with the result that such information is in a constant state of flux and change' (Baddeley, 1986, p. 145).

Such an explanation can account for the loss of to-be-forgotten items but there is a large effect of articulatory suppression and irrelevant speech in these experiments.

This suggests that articulatory rehearsal of most of the items is required. Such an account fails to explain how the rehearsal set is updated. The list length is unknown to subjects and they must therefore assume that N items must be rehearsed until $N+1$ items have been presented. At this point they must shift their rehearsal set. There is no problem, assuming passive storage of the most recent item(s), in losing an item but the addition of a new item to the rehearsal set, in a supraspan list in particular, requires a shift in the rehearsal frame, i.e. the subject must lose the oldest item and add a new one to the other end of the list. This involves assigning new ordinal tags to the items such that, for example, if there is a potential candidate for serial position 2, all other presented items, except for the item that is dropped, must also, simultaneously, be shifted. Thus, if $N = 4$ and a $N+2$ list is presented, for example, N, P, L, Z, Q, Y, the initial rehearsal set, with serial position in parentheses, is (1)N, (2)P, (3)L, (4)Z and the updated set for $N+1$ items becomes (1)P, (2)L, (3)Z, (4)Q and, finally, (1)L, (2)Z, (3)Q, (4)Y for $N+2$. Such reassignment of ordinal tags is not an intrinsic feature of the articulatory loop because the set of items that must be *refreshed* by articulatory rehearsal is different at each update. It is this aspect of the task that probably requires coordination by an executive mechanism. Similarly, by analogy counting probably requires very little executive capacity but complex mental arithmetic requires the coordination of routines that are probably drawn from procedural memory and such coordination is likely to be an executive mechanism.

Baddeley (1986) suggested that the central executive may act as a kind of supervisor involved in the selection of strategies and integration of multiple sources of information. In addition, Morris (1986, 1987) proposed that the central executive is 'coupled' to the visuo-spatial scratch pad during active encoding of spatial material and that this coupling is broken during maintenance rehearsal to liberate executive resources for other tasks after such encoding. The findings of the studies reported here suggest that such decoupling occurs rapidly when the articulatory loop is deployed, and provides one explanation of why it is so difficult to fractionate the central executive/slave system complex. If the executive does indeed possess the ability to redeploy its resources very rapidly to coordinate complex cognitive processing, then it will prove to be extremely difficult to isolate the executive because of its 'time-sharing' capabilities. Thus, slave systems can be dissociated from each other by employing interference activities that are specifically targeted at a given slave system. However, the executive can probably only be isolated by either presenting a demanding dynamic memory task, interfering with the locus of control (Broadbent, 1977) or by searching for appropriate neurological deficits. Executive dysfunction may be detected in populations with neurological impairments that disrupt the strategic aspects of memory processing.

Patients with damage to the prefrontal cortex may provide a useful population to examine for possible executive dysfunction. Fuster (1980), for example, has proposed that the prefrontal areas are important in the temporal organization of processing stages. Furthermore, Shallice (1982) has suggested that one function of the frontal lobes is to 'plan' cognitive activities. Thus, the results of this study are consistent with the neurological literature given that the substrate of the articulatory loop is unlikely to encroach into the frontal areas (see Vallar & Baddeley, 1984, and Vallar & Cappa, 1987, for neuropsychological studies of the articulatory loop). Miller, Galanter & Pribram (1960) anticipated many of these findings when they proposed that 'the memory we use for the execution of our Plans... [is]... a kind of quick-access "working memory"' (p. 65).

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