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Fractionating the Central Executive

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**Fractionating the Central Executive**

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In 1974, Graham Hitch and I proposed an alternative to the then dominant Atkinson and Shiffrin model of short-term memory (STM). We felt that the so-called modal model had difficulty accounting for data from patients with specific STM deficits (Shallice & Warrington, 1970), in accounting for the powerful impact of differential encoding on LTM ( Craik & Lockhart, 1972), and in accounting for a range of our own results obtained using dual task methodology. We proposed instead a system having at least three components, using the term working memory (Miller, Galanter, & Pribram, 1960) to emphasise our concern with the functional role played by this system over and above that of simple short-term storage.

The term working memory (WM) is used to refer to a multicomponent system, capable of both storing and manipulating information, and hence playing a central role in complex cognitive activities such as learning, comprehending and reasoning. The temporary storage of information (STM) is still assumed to be an important function of WM, however, and two of the three subsystems proposed, namely the phonological loop and the visuo-spatial sketchpad, were still primarily regarded as storage systems for verbal and visuo-spatial information respectively. However, the third component, the central executive, was postulated principally as an attentional control system, capable of integrating the two slave systems, of linking them with information from LTM, and of manipulating the resulting representation. In our original formulation, the executive was almost entirely under-specified, being regarded as a pool of processing capacity able to carry out the complex functions that were required to operate and combine the slave systems. It is therefore fair to say that the central executive functioned as a homunculus, the little man in the head who does all the tasks that can not currently be explained by the model.

I have to confess however, that I am rather fond of homunculi, sharing Attneave's (1960) view that they can be very useful, if handled with care. They are, in particular, helpful in allowing one to put on one side important but currently intractable problems, while concentrating on more manageable issues. It is of course important to recognise that they do not offer a solution to a problem, merely serving a holding function.

This continued to be the role played by the central executive until Baddeley (1986), embarrassed at the lack of progress, began to attempt to fill the theoretical void. The strategy employed then and since has been to attempt to specify the roles to be played by the temporary homunculus, trying first to identify the tasks it needs to perform and then to explain how they are in fact achieved. By gradually splitting off and interpreting these functions, it was hoped eventually to reach a point at which the homunculus was no longer necessary, and hence could be pensioned off (Baddeley, 1996).

#### The Problem of Fractionation.

Attempting the strategy of divide-and-rule in the analysis of executive functions is of course far from novel, having been used extensively in the attempt to analyse the functions of the frontal

lobes (Roberts, Robbins & Weiskrantz, 1998). The difficulty comes, however, in successfully achieving this aim.

It is a truism of neuropsychological investigation that dissociations offer a more powerful tool than associations. In the area of memory for example, the most powerful evidence for fractionating LTM and STM came from single case studies of amnesic patients and patients with STM deficits. When required to perform tasks that data on normal subjects suggested were dependent on STM, densely amnesic patients were unimpaired (Baddeley & Warrington, 1970), while patients with grossly impaired STM showed normal LTM (Shallice & Warrington, 1970). The section that follows describes our first steps in attempting to apply the dissociative strategy to the analysis of the central executive.

A major problem in tackling executive processes, however, is the lack of consensus as to exactly what they constitute. Much of the earlier research in this area attempted to capitalise on the probable association between frontal function and executive control, pointed out by Shallice (1982). It is certainly the case that 'frontal lobe syndrome' patients typically show both failure on a range of tasks that can plausibly be assumed to depend crucially on executive control, and damage to the frontal lobes (Shallice, 1988). However, the frontal lobes occupy a very large part of the brain, and it is by no means uncommon to find patients who clearly have lesions in this area that are apparently unaccompanied by cognitive deficit. Furthermore, examples of executive failure may occur in the absence of clear evidence of frontal lobe damage. Both of these suggest that it is unwise to conflate a cognitive deficit with its presumed anatomical underpinning, particularly given that neither of these is well understood.

Baddeley and Wilson, (1988) therefore proposed that the anatomically based term frontal syndrome be replaced by the term dysexecutive syndrome. They suggested that the analysis of this wide array of cognitive symptoms should be studied in their own right, and in parallel with investigation of the neuropsychology of the frontal lobes, while accepting that it is probable that these two lines of investigation will become integrated in due course. A separation between specification at the functional and anatomical levels is, of course, very common in neuropsychology. In the case of memory, for example, our progress would be likely to have been much less had we attempted to define LTM in terms of the damage to a single anatomical structure such as the hippocampus. As the excellent chapter by Stuss and colleagues in this volume indicates, Baddeley and Wilson were by no means alone in proposing such a dissociation between the study of the neuro-anatomy of the frontal lobes and the study of executive function.

We are, however, still left with the question of how to fractionate the central executive. One approach might be to take the tasks that have traditionally been assumed to be associated with frontal function, using them as measures of hypothetical underlying executive processes. However, as these were typically based on studies of frontal lobe lesions, such an approach

seemed likely to lead us back into the structure-function conflation we were trying to escape. We decided therefore to step back and simply speculate on what capacities an executive would need in order to function adequately (Baddeley, 1996).

In the interests of simplicity and tractability, we assumed that the executive was purely a system for attentional control, and did not itself have any storage capacity (Baddeley & Logie, 1999). It was able to focus attention against potentially distracting irrelevant information, to switch attention between two or more stimulus sources or actions, to divide attention in order to perform two concomitant tasks, and finally to interface with LTM (Baddeley, 1996). We hoped to obtain measures of each of these, establishing generality by ensuring that the same basic executive functions could be detected by superficially different tasks using different modalities, and to investigate the separability of such functions using the classic methods of dissociation.

Our principle subject group so far, has been patients suffering from Alzheimer's disease (AD) in whom we identified a particularly marked deficit in executive control, coupled of course with their even more marked deficit in episodic memory (Becker, 1994; Spinnler, Della Sala, Bandera & Baddeley, 1988). We selected patients in the early stages of dementia (MMSE 18-24), a point at which a clear diagnosis was possible, while cognitive capacities were still adequate for the patient to understand and follow instructions for unfamiliar experimental tasks. The exact location of any underlying anatomical deterioration was uncertain. Hence, although such patients offer the potential for studying executive function, they do not constitute an ideal group for the analysis of frontal lobe function.

#### Executive Control and Dual Task Performance.

Our first study occurred at a time when the central executive was almost totally unspecified, being suggested by the simple tripartite model which implied that any task which required the co-ordinated use of the sketchpad and the phonological loop would be likely to make demands on the central executive. We therefore combined a concurrent visuo-spatial pursuit tracking task, in which the patient was required to keep the stylus in contact with a moving spot of light, with a number of other tasks that were assumed to involve perceptual and response systems that had minimal overlap with the tracking task. Recall of span-length digit sequences is our most frequently used concurrent task. By adjusting the speed of the tracking target and the length of the digit sequences, we were able to titrate level of difficulty to a point at which AD patients, age-matched and young control subjects were all performing at the same level of accuracy. When required to combine the two tasks, both young and normal elderly subjects showed a small but equivalent tendency for performance to decline, whereas AD patients showed a marked deficit (Baddeley, Logie, Bressi, Della Sala & Spinnler, 1986).

A subsequent longitudinal study showed that, while the progression of the disease over a period of twelve months had minimal effect on the two tasks performed alone, it led to a clear

and systematic decline in dual task performance (Baddeley, Bressi, Della Sala, Logie & Spinnler, 1991). This contrasted with performance on a task in which subjects attempted to classify words as belonging to one or more categories. Level of difficulty was manipulated by increasing the number of categories. The AD patients performed more slowly overall. Increasing the number of categories slowed response times for all subject groups. However, there was no interaction between subject group and category size, suggesting that an increase in difficulty does not inevitably have a disproportionate impact on the performance of AD patients. The category size effect was, however, relatively small suggesting the need for a much closer examination of the role of level of difficulty.

Reviewing studies of the impact of AD on attentional control, Perry and Hodges (1999) suggest that dual task performance provides the clearest evidence of a differential deficit in AD over and above that of ageing. They note, however, that an alternative hypothesis in terms of lower processing speed in AD patients needs to be investigated more fully. This has recently been attempted in two separate research programmes. Logie, Cocchini, Della Sala and Baddeley (2000) have independently manipulated the level of difficulty, and the presence of a dual task demand. In one study, they investigated the effect of level of difficulty when tracking and digit recall were performed as single tasks. For the digit task, span was established, after which memory was tested at two digits below span, one below, span, and one and two digits above span. The results are shown in Figure 1, from which it is clear that simply increasing the level of difficulty does not differentially impair the performance of the AD patients. In the case of tracking, the standard pretest procedure was used to determine the target speed that resulted in 60-70% time on target. AD patients and young and elderly control subjects were then tested at 50% of this speed, and at 75%, 100%, 125% and 150%. Once again, varying level of difficulty had the same effect on all three groups. Hence, neither task gave any support to the suggestion that AD patients are more susceptible to an increase in difficulty than control subjects.

----- Figure 1 about here -----

In a further experiment, dual task performance was studied using the easiest tracking and digit conditions. Combination of the two tasks led to an overall decrement of 12.6% in AD patients, significantly greater than that found in the elderly (2.71%) or young subjects (3.34%).

Baddeley, Baddeley, Bucks, and Wilcock (1999) also chose to investigate the capacity for dual task performance in AD patients. They attempted to tackle the difficulty hypothesis by comparing the performance of AD patients, age-matched controls and young controls on tasks involving focused or divided attention. One focused task involved reaction time, with level of difficulty studied by comparing simple and choice RT.

Two dual task tests were used. One was essentially a replication of earlier findings, with a visuo-spatial task in which subjects placed crosses in a chain of boxes, combined with a concurrent digit span task. A second experimental task was analogous to the task of a rail passenger reading a magazine in a station and waiting to hear their station name announced. The visual component involved searching an array of pictograms. Each row was preceded by a target, and the subject required to cross out any occurrences of the target on that row, before proceeding to the next row and another target. The auditory task involved listening to a stream of town names for the name 'Bristol', the city in which the testing was carried out; whenever subjects heard the target name they were required to repeat it.

Performance of the AD patients and the two control groups on simple and choice RT showed, as expected, that overall performance was better in the young subjects than the elderly controls, who responded more rapidly than the AD patients. All groups showed faster simple than choice RTs. There was a significant interaction between age and task difficulty, indicating that older subjects were more affected by increasing the number of alternatives. However, there was no evidence for a further interaction between disease and level of difficulty, as predicted by the hypothesis that more difficult tasks are simply more sensitive to AD patients.

When digit span was combined with the visuo-spatial box-crossing task, all three groups were able to maintain speed of box-crossing reasonably well under dual task conditions, although there was an interaction between condition and group, reflecting a small but significant tendency for the patients to work slightly more slowly. As is typically the case, however, performance on the concurrent digit span task showed a clear dual task decrement for patients, but little for either of the control groups.

Figure 2 shows the equivalent data for the task involving visual search and auditory detection. Rate of visual search was clearly influenced both by age and AD, and once again held up reasonably well, although there was a suggestion that the patients were impaired by the concurrent auditory task. However, as Figure 2b indicates, the dual task requirement led to a substantial and significant increase in errors on the auditory detection task in the case of the patients, but not the controls.

----- Figure 2 about here -----

Thus, we again found clear evidence of a dual task deficit in AD patients. The effect of difficulty in the absence of division of attention was shown in the simple and choice RT study. As anticipated, the older subjects responded more slowly than the young, while the AD patients were yet slower. The move from simple to choice reaction time also increased response latency. However, there was no significant interaction between condition and group. The effect of age was at least as marked as the further effect of AD.

The combined data from the various studies of dual task performance in AD patients strongly indicate a particular susceptibility to the requirement to perform two tasks simultaneously, a deficit that does not characterise normal elderly subjects, at least when the level of the constituent tasks is adjusted so as to equate performance across groups in the single task condition. The data from Logie, Della Sala, Wynn and Baddeley (2000) and Baddeley et al (In Press) do not readily fit an interpretation in terms of an overall simple deficit in speed of processing. They suggest a qualitative distinction between the effects of increasing difficulty through requiring dual task performance, and increasing it by increasing the level of difficulty of a single task (Baddeley et al, 1991; Baddeley et al, In Press; Logie et al, 2000).

To what extent however, can these findings be generalized beyond the study of AD? A similar though smaller dual task decrement has been shown using the same paradigm in patients suffering from Parkinson's disease (Dalrymple-Alford, Kalders, Jones & Watson, 1994), while Hartman, Pickering and Wilson (1992) have adapted the paradigm to study the effect of concurrent conversation by a therapist on the motor performance of brain-damaged patients. They found that conversation had no detrimental effect on control subjects, but did impair patient performance, with the effect being more marked in patients with evidence of frontal lobe damage.

The paradigm has also been applied to rehabilitation research by Alderman, Fry and Youngson (1995), who were interested in studying patients within a rehabilitation unit. The unit operated on the basis of a token economy, attempting to reduce antisocial behaviour that was preventing the patients benefiting from therapy. Most patients responded positively to the regime, but a small number did not. Such patients proved to have a particular problem in dual task performance, suggesting the intriguing possibility that the capacity to respond appropriately in social situations might itself involve a form of dual tasking, perhaps for example, requiring one to monitor one's own goals and aims at the same time as taking account of the needs of others.

An additional link between dual task performance and behavioural dysfunction came from a study attempting to examine the relationship between dual task performance deficit and frontal lobe damage (Baddeley, Della Sala, Papagno & Spinnler, 1997). Patients identified as having clear anatomical evidence of damage within the frontal lobes were tested on the Wisconsin card sorting test and on a test of verbal fluency. They were also independently categorized by two judges as to whether they showed the disorganised behaviour sometimes associated with frontal lobe damage. All subjects then performed two tasks, a perceptual-motor task involving crossing out a chain of boxes, in each of which a cross had to be written, and an immediate memory task involving a series of digit sequences of span length. These tasks were performed singly and in combination. When the groups were split on the basis of the ratings of dysexecutive behaviour, there was clear evidence for an association between dual task performance and disordered behaviour. There was in addition an overall impairment in performance on both the WCST and verbal fluency, but no suggestion that either of these was

differentially associated with dysexecutive behaviour. Given that the findings of this study and of that of Alderman et al were to some extent unexpected, this issue clearly requires further investigation before drawing any firm conclusions. If replicated, then it might still simply reflect separate cognitive and behavioural functions that happen to depend on anatomically adjacent areas. An intriguing possibility however, is that the capacity to perform two tasks at the same time is an important and pervasive component of normal social interaction, perhaps operating through the need to combine ones own needs and aims with an appreciation of those of others.

#### Executive Control and Task Switching.

A third possibly separable executive function proposed was that of a capacity to switch attention from one task to another (Baddeley, 1996). Despite some highly innovative studies by Jersild in 1927, and a brief revival of interest some 50 years later (Spector & Biederman, 1976), the study of task switching has only begun to receive the attention it would appear to deserve, following an extensive series of experiments by Allport, Styles & Hsieh (1994), which has gone on to stimulate considerable related work (e.g. Los, 1996; Meiran, 1996; Rogers & Monsell, 1995).

Following up the suggestion that task switching might depend on a specific and separable component of the central executive, we decided to investigate the issue using dual task methodology. We selected and simplified an arithmetic task initially developed by Jersild. In our version, subjects were presented with a column of single digits printed on a sheet of paper, and were required either to add 1 to each digit, or to subtract 1. In the crucial switching condition, they were asked to alternate between adding and subtracting, in each case moving down the list as rapidly as possible without making errors.

We argued that if there were an important switching component to the executive, then requiring subjects to perform simultaneously another switching task should massively impair performance. Baddeley, Emslie, Kolodny & Duncan (1998) had in fact, developed just such a task, based on modifying the trails test. It involved the recitation of two overlearned sequences, numbers and letters, either as single sequences, (A, B, C, D, E, F, etc.; 1, 2, 3, 4, etc.) or in alternation (1, A, 2, B, 3, C, 4, D, etc.). Evidence for the executive nature of the task came from combining it with a random keyboard generation task. Our verbal version of the trails task substantially disrupted random generation; indeed, degree of disruption was virtually equivalent to that resulting from performing a concurrent fluid intelligence test. As we planned to use this verbal trails task in combination with the concurrent arithmetic, we felt it necessary to avoid using numbers, opting instead for two other overlearned sequences, namely days of the week and months of the year. Hence in the blocked condition, subjects would simply recite Monday, Tuesday, etc., or January, February, March, etc., while in the verbal trails condition they were required to alternate (Monday, January, Tuesday, etc.). Such a task does, of course, involve both alternation and articulatory suppression, making it necessary to include a further control

condition in which subjects recited either the days of the week, or the months of the year, without the requirement to alternate.

Our design, therefore, looked at the cost of switching between addition and subtraction when arithmetic was performed alone, when performed while simultaneously reciting a well-known sequence, the months of the year or days of the week, and while alternating days and months. If there is indeed a specific executive function concerned with switching of attention, then we might expect massive interference from the verbal trails task, compared to little or no effect of articulatory suppression. Finally, our study included one further small but important variable. Spector and Biederman (1976) reported that although arithmetic switching caused a substantial slowing in performance when they had to remember to alternate in the absence of plus and minus signs, accompanying each digit with the appropriate sign virtually eliminated the switch cost. We therefore ran two studies, one in which each digit was followed by the appropriate sign, and one in which the signs were omitted. The results of our two studies are shown in Figure 3.

----- Figure 3 about here -----

Consider first Figure 3a, performance with signs present. Unlike Spector and Biederman, we did obtain a clear switching effect. Furthermore, performance was indeed impaired by our concurrent verbal trails task, although not dramatically so. Figure 3b shows performance when the plus and minus signs were omitted; first of all, there was a much more substantial switching effect, as indeed Spector and Biederman would have predicted. The concurrent verbal trails task had a major effect on performance, but note that its effect occurred for both blocked and switching conditions, suggesting that it impaired the basic arithmetic task as well as the capacity to switch. Our most unexpected finding, however, came from the articulatory suppression condition; although suppression had little effect on blocked performance, it had a marked impact when switching was required.

How should we interpret these findings? First of all, although we obtained a consistent switching cost, when the need to remember what to do next was removed by providing signs, the cost was small, despite a demanding concurrent task. Our major effects appear to come from the requirement to maintain and operate the switching programme, an effect that is markedly increased by concurrent articulatory suppression. We will discuss these in turn.

Our results provide some support for a role of the central executive in task switching. However, the evidence for a specific effect on switching per se is weakened by the impact of our verbal trails task on speed of performance under the blocked condition, when switching is not required.

In contrast to our lack of success in throwing light on the proposed central executive switching process, our results do seem to have strong implications for another important issue. Whenever subjects come into a psychological laboratory to take part in an experiment, they will need a set of instructions as to how they should respond to the experimental material that will be presented. In the case of bright young students, they typically have little difficulty in absorbing quite complex instructions, going on to retain them and operate them at speed. How do they do this? In a very thoughtful article, Monsell (1996) offers this as his contribution to a book on unsolved problems of psychology. At first sight, our own study suggests that the phonological loop may play an important role in maintaining such internalised plans or programmes, However, our suppression task, reciting the months of the year, while an appropriate control for the verbal trails task we used, might itself be relatively demanding. We therefore carried out a further study in which suppression simply involved repeatedly uttering the word 'the'. We obtained the same results, although the effects were less marked. This suggests that holding and operating the alternation programme may well involve processes beyond simple articulatory rehearsal. The question of what these might comprise is discussed in the next section.

Vygotsky (1962) suggested that verbalization may be an important mechanism for the control of action, a view that was subsequently extensively supported by Luria in studies of both children and of patients with frontal lobe damage (Luria, 1959a, b). Given that such verbal control programs need to operate over at least the duration of an experimental session, they would appear to implicate the fourth function attributed to the central executive by Baddeley (1996), namely the capacity to interface with LTM.

#### Linking WM and LTM: The Episodic Buffer.

Over the years, although the concept of WM has proved applicable to a very wide range of data, there has been a steady trickle of results that were not easy to accommodate within the existing framework. This was particularly so once the decision had been taken to regard the central executive purely as an attentional control system, without itself having any storage capacity (Baddeley, 1996; Baddeley & Logie, 1999). Although somewhat diverse, most apparent anomalies fall into two related categories, namely that of integrating information from the two slave systems, and interfacing with LTM.

The problem of integration is found even in relatively simple tasks such as the immediate serial recall of visually presented verbal material. The presence of a powerful effect of phonological similarity indicates that such tasks typically rely heavily on phonological coding. When visual presentation is accompanied by articulatory suppression, the phonological similarity effect disappears and performance is markedly reduced. However, subjects can still remember 4 or 5 digits, and even patients with grossly defective phonological STM can typically remember at least 3 or 4 digits when presented visually (Shallice & Warrington, 1970).

A small but consistent visual similarity effect can also be found in serial verbal recall (Logie, Della Sala, Wynn & Baddeley, 2000). Furthermore, digit span is greater when visually presented items comprise Arabic numerals (7, 3, 9, etc.) than when they are presented as words (seven, three, nine, etc.). The possibility that this is due to the greater visual complexity of the digit words is suggested by the fact that the effect was eliminated by a concurrent visuo-spatial task (Chincotta & Underwood, 1997a, b). All of these results imply a capacity to combine information from visual and verbal sources; the WM model as outlined by Baddeley and Logie (1999) has however, no mechanism for achieving this combination.

The same issue occurs even more acutely in the recall of sentential material. Subjects can typically recall about 5 unrelated words, or about 16 words if they are combined into a meaningful sentence, well beyond the capacity of the phonological loop (Baddeley, Vallar & Wilson, 1987). Thus there appears to be a synergistic relationship between material held in the phonological store and that held in semantic and linguistic form, presumably in LTM.

A similar problem is raised by the recall of a prose passage such as the Anna Thomson story from the Wechsler Memory Scale (Wechsler, 1945). Recall is of course measured in terms of gist rather than verbatim, and in an intelligent normal subject would comprise about 15 idea units. Performance is typically tested immediately and after a filled delay of about 20 minutes, at which point amnesic patients are likely to recall virtually nothing. On immediate recall, however, although many patients performed poorly, a few performed at a virtually normal level (Wilson & Baddeley, 1988). How could such normal performance be achieved by a densely amnesic patient? Clearly the recall of 15 idea units is well beyond the capacity of the phonological loop; indeed the very process of recall would surely disrupt retention of later items within the phonological store, since it would introduce a filled delay of many seconds. Our suggestion (Baddeley & Wilson, submitted) is that such patients were relying upon temporarily activated representations in LTM, a view not unlike that assumed by the concept of long-term working memory proposed by Ericsson and Kintsch (1995). Like them, we assume that the comprehension of a complex prose passage involves the activation of long-term representations at levels ranging from individual words, through phrases to general concepts and higher level schemata such as those proposed by Schank (1982). We assume that integrating and maintaining such novel representations is likely to place heavy demands on executive processing. In line with this view, Baddeley and Wilson found that good immediate prose recall in amnesic patients occurs only when intelligence and/or executive processes are spared. Patients suffering from AD, who typically show executive deficits, were found to be almost uniformly poor on immediate as well as delayed recall.

It appears to be the case, therefore, that given preserved intellect and executive control, even densely amnesic patients are able to maintain temporarily a relatively complex semantic structure. Unlike normal subjects however, once attention is withdrawn, this structure appears to dissipate rapidly. Other similar examples have been reported in other domains. For

example, Endel Tulving (personal communication) reports the case of a densely amnesic patient who retained the capacity to play bridge. Not only could he remember the contract throughout a game, but he was able to keep track of what cards had been played sufficiently well for him and his partner to win the rubber. This, like the preserved prose recall, points to some form of temporary activation, based on LTM but usable even in patients with gross disruption of episodic long-term retention.

The examples just described represent some, but by no means all of the pieces of evidence that do not fit readily into the 1999 version of the three component working memory model. One could of course abandon the model and start again, but given its success over the last 20 years in accounting for a very wide range of data, this seemed premature. Instead, a fourth component was suggested, namely the episodic buffer.

The episodic buffer is assumed to be a limited capacity storage system, capable of temporarily holding and manipulating information registered in terms of a multi-dimensional code (Baddeley, 2000a; b). It is termed episodic to reflect its capacity to hold integrated episodes that extend both spatially and temporally. It is a buffer in the sense that it offers a multi-dimensional code that allows information from different sub-systems to be integrated, and linked to LTM. Such a multi-dimensional capacity tends to be computationally demanding, hence the limited capacity of the buffer (Hummel, 1999). The buffer is assumed to be controlled by the central executive, using conscious awareness as a major retrieval strategy (Baddeley, 1993; Baddeley & Andrade, 1998; 2000). This modified version of the WM model is shown in Figure 4.

----- Figure 4 about here -----

Whereas our initial approach to WM emphasized the importance of fractionation, developing methods of establishing separate subsystems, the principal function of the episodic buffer involves integration. As such, it refocuses attention on Miller's classic concept of chunking, whereby storage capacity is increased by integrating a number of disparate features into a single whole (Miller, 1956). Chunking can, of course, operate at a whole range of levels extending from the role of rhythmic cues in enhancing auditory digit span (Ryan, 1969) through to the use of expertise to chunk complex arrays such as chess positions when viewed and recalled by chess masters (Saariluomi, 1995). It seems unlikely that all of these will be attentionally demanding, or indeed are likely to occur in the episodic buffer. Luck and Vogel (1997), for example, present evidence to suggest that subjects are capable of encoding and retaining multiple visual dimensions when they represent the features of a single object, whereas when represented across a different range of objects, performance is much poorer. The episodic buffer is much more likely to be involved in the more complex aspects of chunking, where executive processes are likely to play an important role, creating new chunks from previously unrelated constituent features.

Postulating a new component of WM raises a number of questions. It is important, for instance, to determine the limits of the system, in particular separating the proposed multi-dimensional system from the existing slave systems. This should be possible to achieve by using dual task measures, investigating tasks that interfere with one slave system but not the other, and those that influence both (Baddeley & Andrade, 2000). The study of carefully selected single cases with specific deficits to one or other of the component systems of working memory should also be very helpful in this respect.

Another important issue concerns the relationship between the episodic buffer and LTM. Cowan (1999; in press) makes similar assumptions about the utilization of LTM via a limited capacity attentional control system analogous to the central executive. However, he does not postulate an additional temporary store, presumably on the assumption that the activation in LTM is sufficient. However, given that access to LTM appears to be attentionally relatively undemanding (Baddeley, Lewis, Eldridge & Thomson, 1984; Craik, Govoni, Naveh-Benjamin & Anderson, 1996), it is not clear why performance of tasks that are assumed to require the episodic buffer appear to be so dependent upon executive capacity. It is also not clear how a system that simply reactivates existing material could be capable of creating and manipulating new representations. Consider for example, the concept of a female elephant playing ice hockey. Although this is an unlikely concept, most people appear to be able to create it, and, furthermore, to use it to make novel decisions. What might be the best position for such a team member? She would be capable of delivering a formidable body check, but might she be even more useful in goal?

I suggest that the episodic buffer serves as a system not only for representing the environment and making it accessible to conscious awareness, the classic binding problem, but also for utilizing past experience in order to model the future. Simply activating LTM seems unlikely to achieve this goal. A possible solution might appear to be to suggest that such manipulation involves the maintenance of 'addresses' for representations in LTM. However, it could be argued that this is not an alternative to a buffer, so much as a speculation as to the process underlying the operation of the episodic buffer, a necessary later step, but not one that needs to be taken at this point. It does however, lead on to the important question of how the episodic buffer might conceivably be realised neurobiologically.

First of all, it seems unlikely that the episodic buffer will be represented by a single specific anatomical region or structure. Given that one of its essential functions is to link together many different codes, it must at the very least have multiple connections. Furthermore, if this system is as important as suggested, it seems likely that evolution would have built in a certain amount of anatomical redundancy to increase its robustness against potential brain damage.

There is of course, considerable interest in mechanisms that might potentially solve the binding problem. One interesting line of research stems from the suggestion that synchronised firing might provide a way of linking multiple systems (Singer, 1999). Another possibility is through single cells that respond to the co-occurrence of two or more codes (see Fuster, Chapter --). At a more system-based level, it seems likely that areas within the frontal lobes will play a crucial part in the capacity to integrate concepts (Hummel, 1999).

A recent study using fMRI presents results that fit neatly into the concept of an episodic buffer. Prabakaran, Narayanan, Zhao & Gabrielli, (2000) required subjects to retain over a brief delay either letters or marked spatial locations. In a third condition, they were required to recall the locations, together with the letters, with the two sets of stimuli presented in parallel. In a fourth condition two sets of stimuli were combined by displaying one letter in each location. In the first three conditions, presentation of the letters activated areas associated with the phonological loop, locations involved areas associated with the sketchpad, while the third condition involved both. However, when the letters and spatial locations were integrated, a separate frontal area became active, whereas previously active areas became less so. The authors conclude “The present fMRI results provide evidence for another buffer, namely one that allows for temporary retention of integrated information.” (Prabhakaran et al, 2000, p. 89.)

One major feature of the episodic buffer concept is its emphasis on the important issue of how information is chunked. Does it represent one, two or many different processes? How is chunking related to the more general concept of binding, and how can it best be studied? Is the capacity of the buffer set by the number of chunks it can hold (Baddeley, 2000a; Cowan, In Press), and if so, can we devise a convenient measure of episodic buffer span?

### Conclusions.

The concept of working memory is multi-faceted and functionally defined, and as such is unlikely to map in a simple way onto an anatomical structure such as the frontal lobes. However, it is clear that the frontal lobes play an important role in integrating information from many other areas of the brain, and are crucially involved in its manipulation for purposes such as learning, comprehension and reasoning. Given that these are precisely the roles attributed to WM, it seems likely that the functional and anatomical approaches will continue to develop synergistically, as the complex functions assigned to WM are tackled using an increasingly sophisticated armoury of new psychological and neurobiological techniques.

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## **Figure Captions**

### Figure 1

Effect of level of difficulty on the performance of patients suffering from Alzheimer's disease, and young and elderly control subjects. The difficulty of a digit span task was adjusted so that all three groups were matched under the standard condition, with performance tested at levels ranging from span-2 to span+2 digits.

### Figure 2

A dual-task performance in AD patients, elderly and young control subjects. Figure 2a shows performance on a visual search task performed alone, and in combination with an auditory detection task. Figure 2b shows the errors in auditory city name detection under single and dual-task conditions.

### Figure 3

Performance on an arithmetic switching task involving alternating addition and subtraction as a function of concurrent task. The tasks involved a base-line control, an articulatory suppression condition, and a condition that itself involved alternation. Figure 3a shows performance when plus and minus signs are present, Figure 3b when they are absent.

### Figure 4

Modified version of the working memory model that includes suggested links to LTM, together with a new component, the episodic buffer, as proposed by Baddeley (2000a).

Figure 1

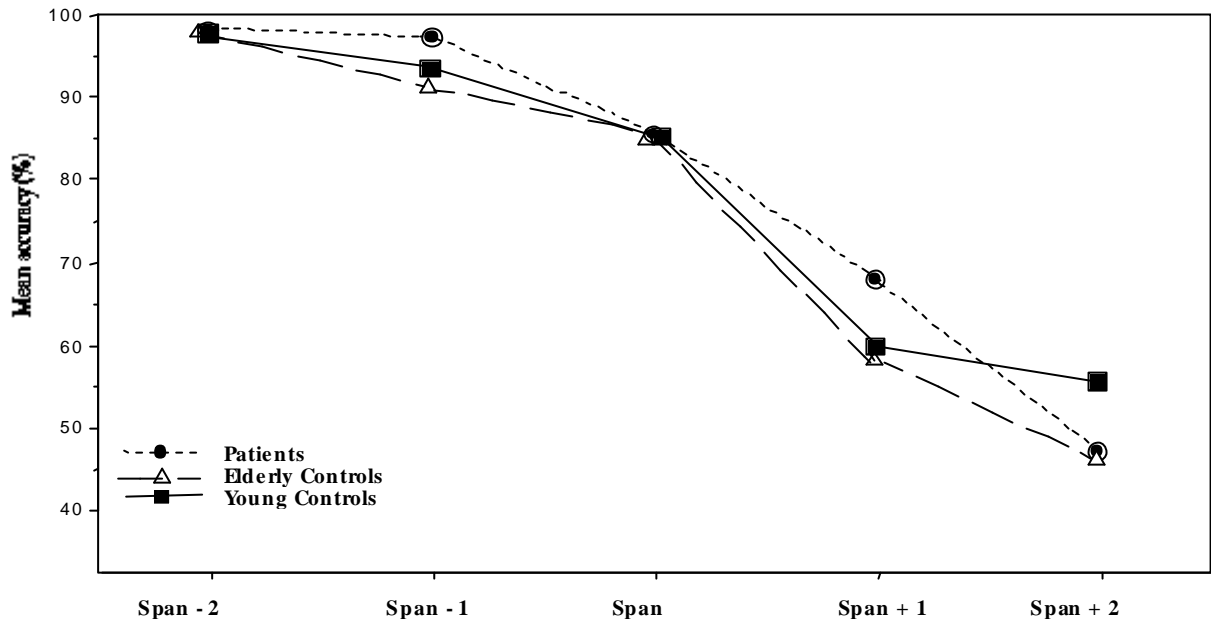
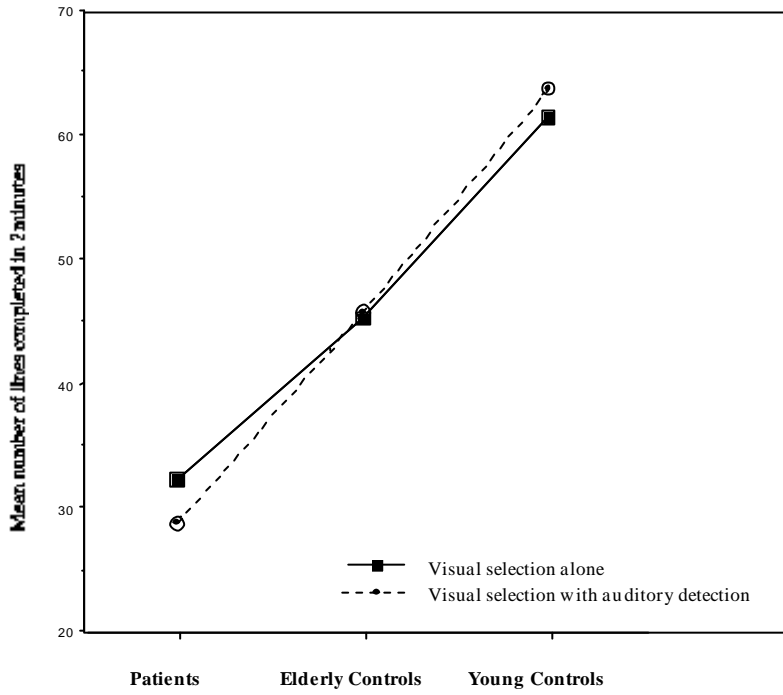
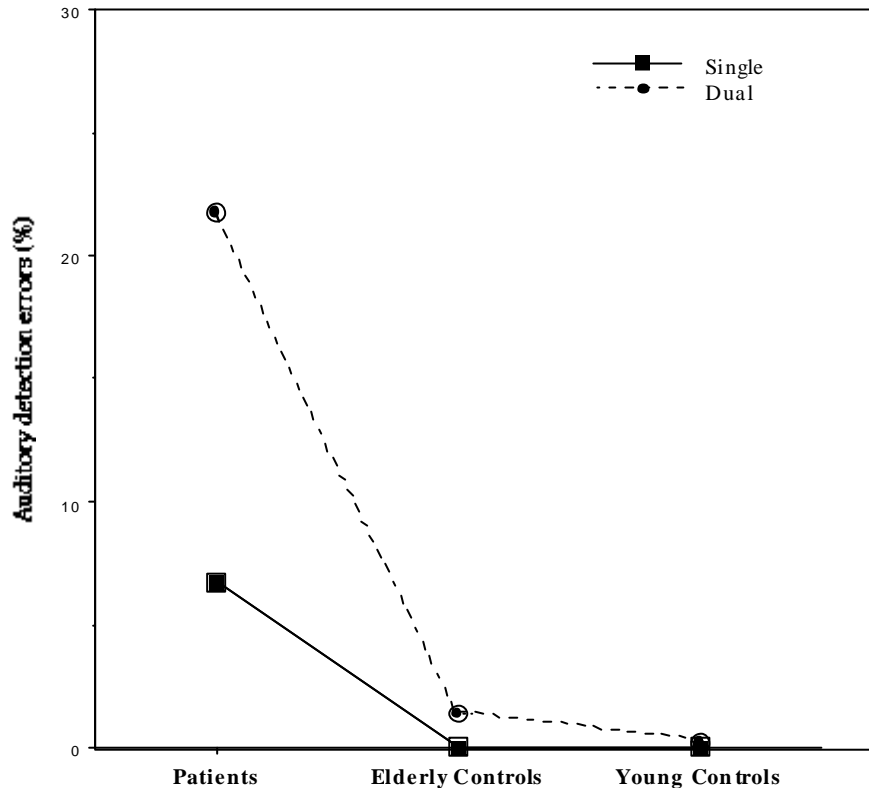


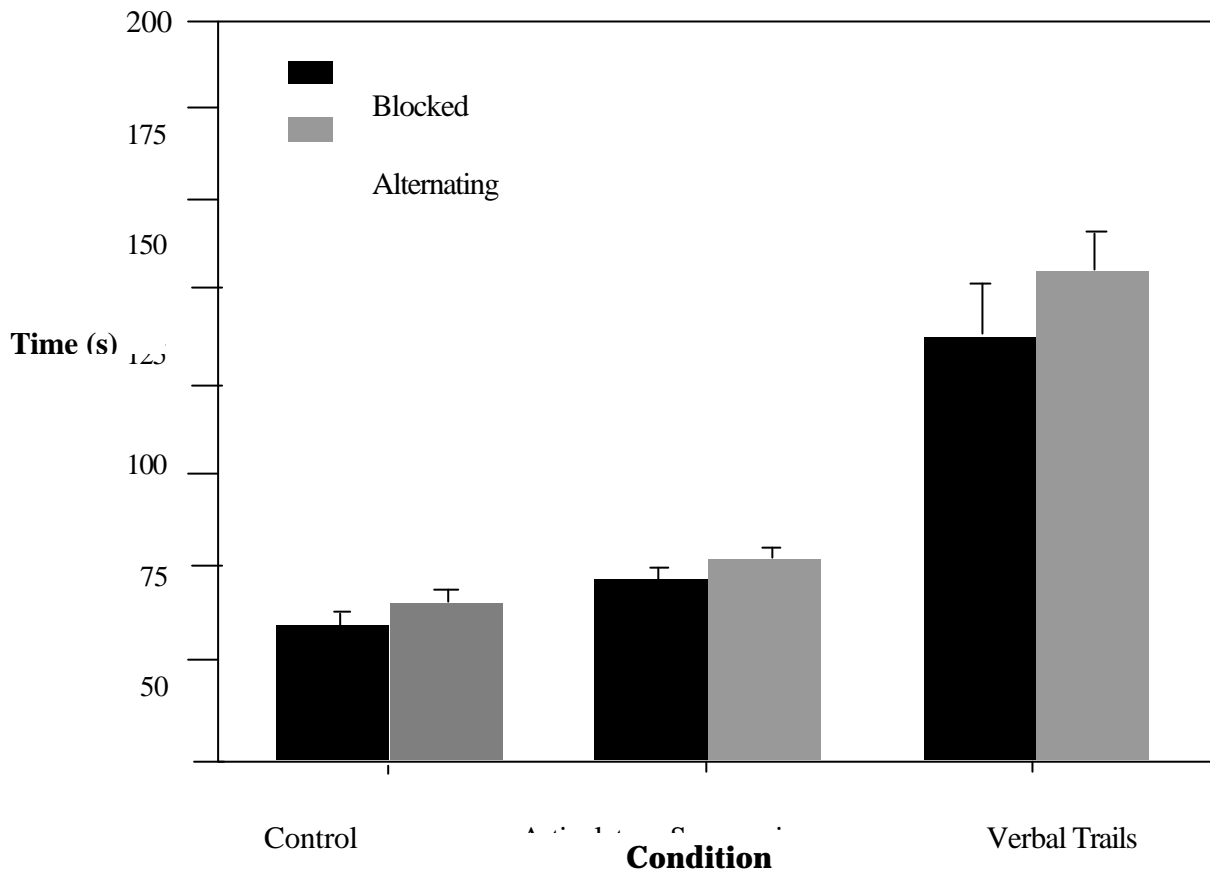
Figure 2a



**Figure 2b**



**Figure 3a**



**Figure 3b**

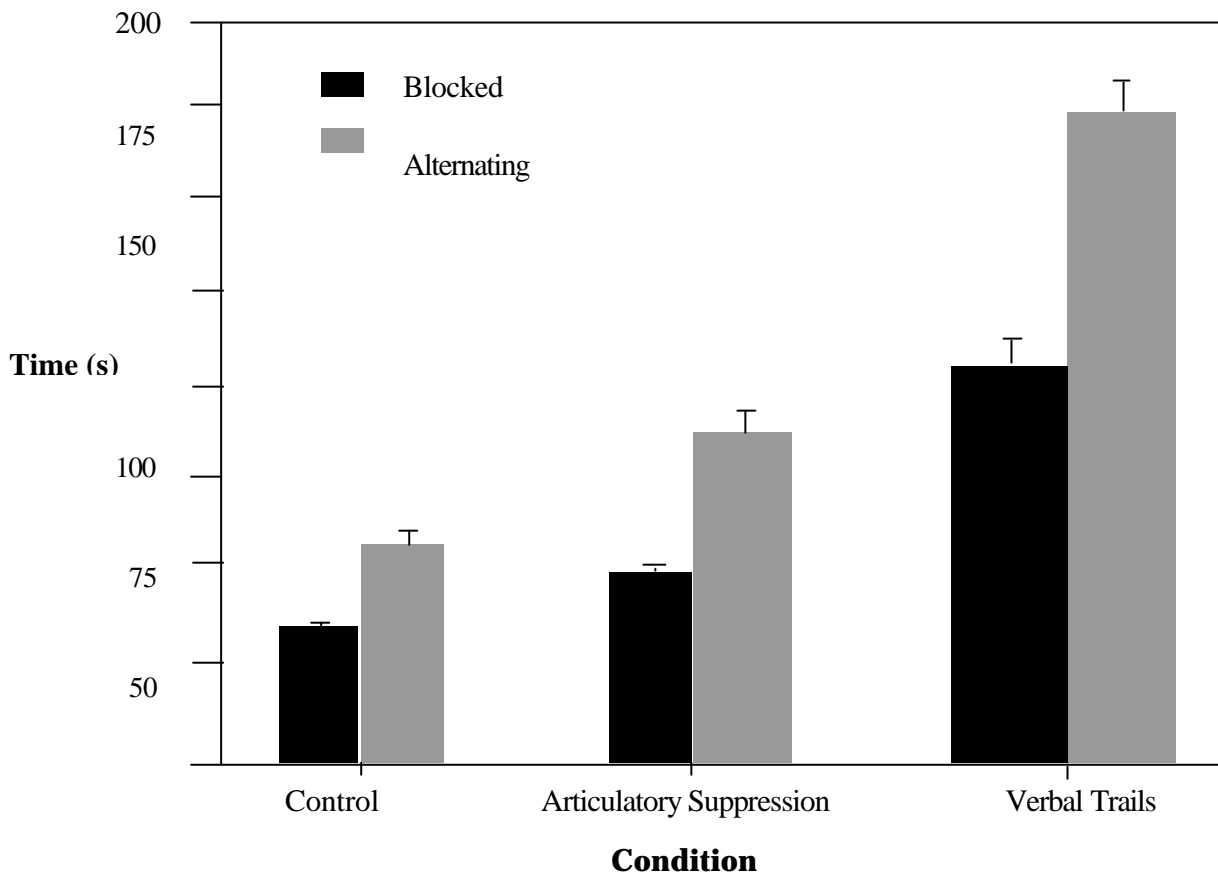


Figure 4

