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Working Memory and Executive Control [and Discussion]

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Working memory and executive control

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SUMMARY

A major problem in analysing the executive processes that seem to depend upon the prefrontal cortex stems from the absence of a well developed cognitive model of such processes. It is suggested that the central executive component of an earlier model of working memory might provide a suitable framework for such an analysis. The approach is illustrated using one proposed component of executive control, namely the capacity to combine two concurrent tasks. The application of the approach to patients suffering from Alzheimer's disease, and patients with acquired brain damage is discussed. Finally, a study is described in which the dual task performance of patients with known frontal lesions is shown to be associated with observed behavioural problems. The paper concludes with the discussion of the prospects for extending the approach to include a range of other executive processes, and to the way in which such an analysis may subsequently lead to a more integrated model of the central executive, and a better understanding of its relationship to the prefrontal cortex.

1. INTRODUCTION

The so-called 'frontal syndrome' is one of the most dramatic and readily recognisable neuropsychological behaviour patterns involving 'disturbed attention, increased distractibility, a difficulty in grasping the whole of a complicated state of affairs...well able to work along routine lines...(but)...cannot learn to master new types of task' (Rylander 1939, p. 20). While this pattern is classically associated with frontal lobe damage however, by no means all patients with damage to the frontal lobes show such behaviour, and where deficits do occur, the pattern of deficits will typically vary from one patient to another.

The classic neuropsychological approach has been to attempt to use lesion data, mapping the location of the lesion onto the nature of the deficit (Milner 1964; Reitan & Wolfson 1994). While this has certainly had some success, the approach is limited by the lack of any obvious coherent pattern in the tasks impaired by frontal damage, which range from concept formation and verbal fluency through the capacity for making cognitive approximations to judgments of recency and the performance of various complex learning tasks (Stuss & Benson 1986). Attempts to look for meaningful clusters of tasks within this array using factor analytic techniques have in general proved disappointing: the various tasks tend to correlate modestly but significantly, without falling into any very clear pattern (Della Sala *et al.* 1996*a*). Furthermore, none of the classic 'frontal' tests seem to capture the frequent gross behavioural derangements that typify patients with frontal lobe damage (Harlow 1868). Indeed dissociation between such tests and behaviour have frequently been reported (Eslinger & Damasio 1985; Shallice & Burgess 1991; Brazzelli *et al.* 1994).

We suggest that these difficulties stem in part, at least, from the failure of cognitive psychology to provide an adequate characterization of the executive processes that form one of the principal functions of the frontal lobes, and we describe below the early stages of one attempt to remedy this.

2. SEPARATING ANATOMY FROM FUNCTION

We would suggest first of all that the very use of the term 'frontal syndrome' compounds the problem by stressing anatomical location rather than function and potentially interferes with its solution. It is both common and useful for neuropsychological syndromes to be defined functionally rather than anatomically. We talk about aphasia, dyslexia, dysgraphia, agnosia and amnesia, accepting that in many cases the exact anatomical underpinning of these disorders represents an important but separate question from their functional analysis. We would suggest that this is highly appropriate. There is no good evidence to suggest within the amnesic syndrome for example, that patients who are amnesic following hippocampal damage are necessarily functionally different from those whose damage is based on the mammillary bodies or indeed from temporal lobe damage, despite many attempts to argue for such differences. It is also the case that examples of 'frontal' behaviour may occur in the absence of frontal localization. Examples include generalized infections such as syphilis, where behaviour shown by Nietsche was distinctly 'frontal' (Kaufman 1974), or in metabolic diseases such as porphyria which led to the 'madness' of King George III (Bennett 1995).

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The approach to be described developed from an attempt to understand working memory, the system necessary for holding and manipulating information while performing a wide range of tasks including learning, reasoning and comprehending (Baddeley & Hitch 1974). Our studies of the functioning of normal subjects prompted us to propose a sub-component of working memory, the central executive, that was responsible for attentional control of working memory. In attempting to conceptualise it in more detail we were strongly influenced by Shallice's (1982) paper in which a model of the control of action is proposed and related to the functioning of the frontal lobes and the breakdown of behavioural control in the frontal syndrome (Baddeley 1986). For a number of reasons however, we were anxious to dissociate the functional from the anatomical aspects of the executive concept.

While the work described by Shallice strongly suggested that bilateral frontal damage might disrupt executive processes, we did not wish to preclude the possibility that other parts of the brain might be involved. Indeed, given that executive processes involve communication between subsystems located elsewhere in the brain, it seemed entirely possible that they could be disrupted before or after the involvement of frontal systems. Given that the frontal lobes occupy a large proportion of the cortex, it seemed entirely possible that they are concerned with functions other than executive processing, with the result that frontal lobe damage need not necessarily lead to executive deficits.

A further constraint was entirely practical. We often did not have precise and accurate anatomical information about many of the patients we studied. One can of course continue to use the 'frontal' label, as indeed is often the case in the neuropsychological literature for patients who show a clear pattern of executive deficit, but to do so assumes the very relationship between anatomy and function that we are trying to test. For that reason we introduced the term dysexecutive syndrome as a functional description of a pattern of behaviour that explicitly leaves open its anatomical underpinning (Baddeley 1986; Baddeley & Wilson 1988). Note that this terminological distinction does not deny the importance of a more traditional anatomically-based approach, in which attempts are made to investigate the function of specific anatomical structures. It does however suggest the need for a parallel approach that emphasises a functional analysis, which can then as a separate step be related to brain structure. Both the structure and function of the executive system is known to be highly complex: attempting to solve both simultaneously may result in a problem with too many unknowns.

3. ANALYSING THE DYSEXECUTIVE SYNDROME

Having made this decision to separate the functional from the anatomical, we were left with a major problem, namely that the central executive was by far the least understood component of working memory.

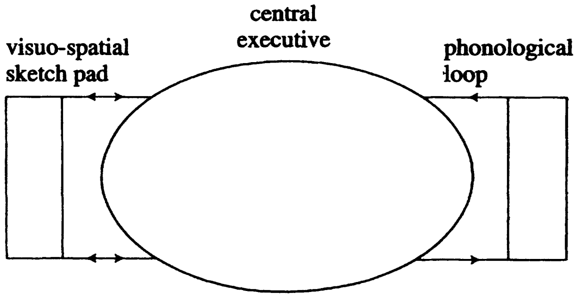

Figure 1. The Baddeley & Hitch (1974) model of working memory.

The problem was highlighted by an attempt to analyse the cognitive dysfunction associated with Alzheimer's disease. An initial study of patients suffering from dementia of the Alzheimer Type (DAT) suggested that in addition to the clear deficit in episodic long-term memory, there appeared to be an impairment in working memory that was most readily attributable to the central executive (Spinnler *et al.* 1988). How should one investigate it? It was tempting to opt for using the classic frontal lobe measures, but to do so would mean that our argument for separating the functional from the anatomical was merely cosmetic. We therefore decided to use the Baddeley & Hitch working memory model to postulate functions that would certainly be required if the model were to operate along the lines implied. We began with a very obvious prediction that is suggested by the representation of the model in figure 1, where the central executive is seen as coordinating the operation of two subsidiary slave systems, the phonological loop which deals with speech based information, and the sketchpad which handles visuo-spatial information. We argued that a defective executive should have difficulty in coordinating the simultaneous operation of these two systems, with the result that dual-task performance should be particularly susceptible to the effect of DAT.

Our first study combined verbal processing with a visuo-spatial task in which subjects attempted to keep a stylus in contact with a moving spot of light; by varying the speed of movement the task could be adjusted so that equivalent levels of accuracy were achieved by our DAT patients and by age-matched and young control subjects. In one study, subjects combined tracking with a digit span task in which they were required to repeat back sequences of numbers, with the length of sequence set so that the error rate was constant across the three groups. When the two tasks were combined, the young and elderly controls performed in a similar manner, suggesting that age per se does not markedly influence the capacity to combine tasks, given that level of difficulty is appropriately adjusted. In contrast, DAT patients showed a marked decrease in performance levels on both the digit span and the concurrent tracking, when required to combine them (Baddeley *et al.* 1986).

A subsequent longitudinal study required DAT patients and controls to perform the tracking and digit span tasks singly and in combination on successive occasions separated by six months (Baddeley *et al.*

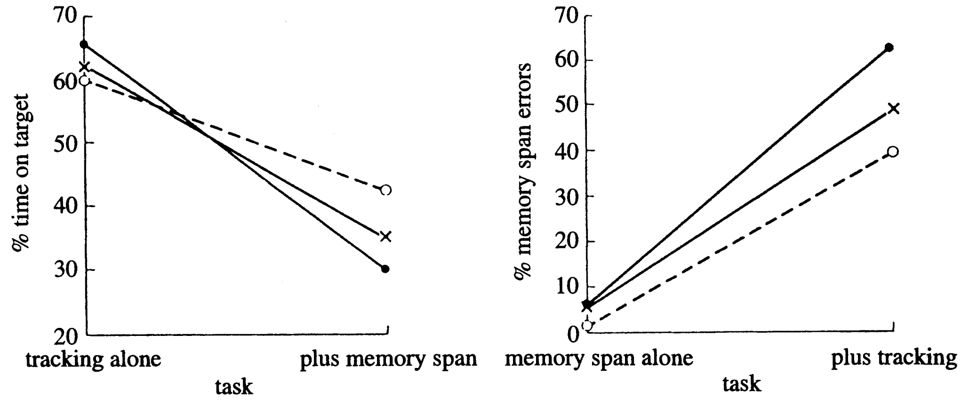

Figure 2. Longitudinal decline in the capacity of DAT patients to combine tasks. (*a*) Effects of memory span on tracking; (*b*) effects of tracking on memory span errors. Patients were tested at six-monthly intervals (open circles denote test 1; crosses denote test 2; closed circles denote test 3); performance on the individual tasks when performed alone was maintained, but both tracking and serial digit recall decline over time, when concurrent performance was required. (Data from Baddeley *et al.* 1991).

1991). As figure 2 shows, the capacity to perform either of the tasks singly showed little or no deterioration, while combined performance showed a steady decline over the three successive tests.

While we were pleased with the results obtained, we were concerned about the generality and the logistic practicality of the procedure used. The tracking task in particular was problematic since it requires a light pen that is not a standard piece of most people's laboratory equipment, together with a program which we found did not readily transfer even to other computers that were nominally identical. We therefore began the search for a paper and pencil alternative to tracking. After a surprisingly long and frustrating search, we eventually developed a task in which the subject is required to place a cross in a chain of boxes arrayed on a response sheet. Having practised the task, subjects are required to fill as many boxes as possible in two minutes. The digit span task then involves selecting a length at which the subject recalls the sequence virtually perfectly, followed by a two minute test run in which tasks are performed simultaneously (Della Sala *et al.* 1995).

The test was validated using a sample of 12 DAT patients and 12 control subjects. Of 13 subjects originally tested within the presumed AD group, all but one showed a decrement in span when combined with tracking that was greater than that obtained in any of the control subjects. The atypical subject subsequently proved not to have a progressive neurological disease and was excluded. Tracking performance showed a similar but less clear cut tendency for patients to show a greater dual task decrement than controls, although this did not reach significance (Della Sala *et al.* 1995).

The same task was used by Greene *et al.* (1995) in a study comparing minimally and mildly impaired DAT patients with age-matched control subjects. Again, there was a clear tendency for the combined task to be particularly susceptible to the disease, whether in the minimally or mildly impaired group, but in contrast to the Italian subjects in the Della Sala *et al.* study, these patients showed their principal decrement on the tracking task. The reason for the discrepancy is not clear, but could stem from the rather higher proportion of memory tasks within the Greene *et al.* study, which may have suggested to the patients that memory performance was more important than tracking. It is worth noting that had the differences in strategy occurred between different patients within the two studies rather than between studies, it is possible that neither of them would have demonstrated a statistically significant difference between the two groups on any single one of the component tasks, thus highlighting the need for a score that combines both of the concurrent tasks. Unfortunately, deriving such a score is likely to depend crucially on the particular assumptions underlying the method of combination. Ideally, such a score should be based on a more detailed analysis of the processes underlying performance at different levels of difficulty, together with an understanding of the process involved in combining them. This is likely to demand a substantial research effort, and in the meantime the following formula has been proposed:

$$mu = \left[1 - \frac{P_m + P_t}{2}\right] \times 100$$

where mu is the combined dual task score, P_m is the proportional loss in span performance between single (P_s) and dual task (P_d) conditions, $((P_s - P_d)/P_s)$ while P_t is the equivalent proportional tracking document (Baddeley *et al.* 1996). When this formula was applied to the validating study, there was a clear separation between performance of DAT patients and control subjects.

One potential theoretical objection to the claim that dual task performance is particularly vulnerable to DAT stems from the suggestion that the results are a simple reflection of level of task difficulty. Baddeley *et al.* (1991) attempted to test this hypothesis by manipulating difficulty within a categorization task by increasing the number of sorting alternatives. While performance deteriorated with the progress of the disease, there was no evidence that the deterioration was particularly marked for the harder conditions, as would be predicted by an interpretation of our earlier results in terms of level of difficulty. A further problem

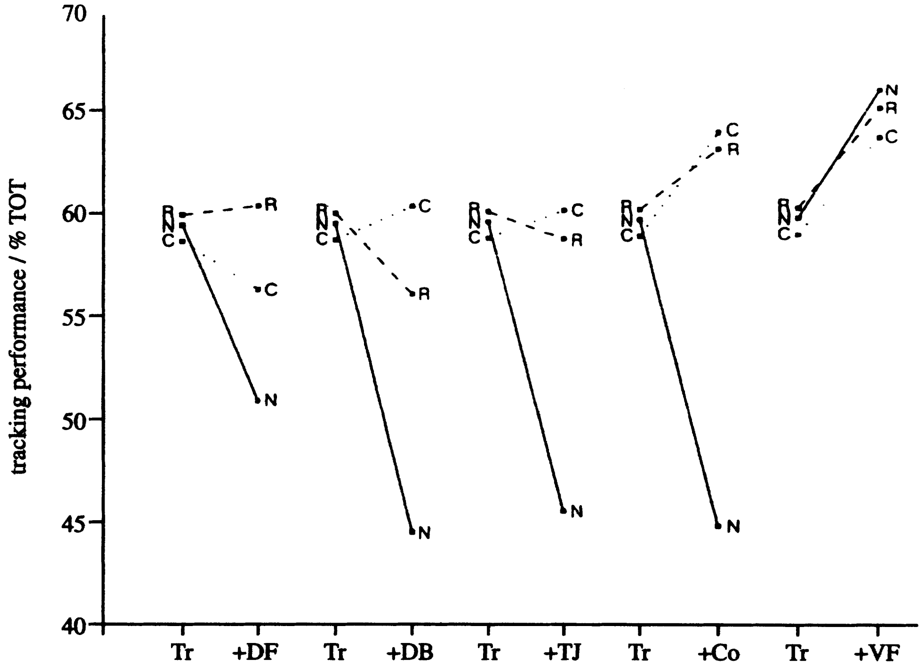

Figure 3. Percentage time on target during tracking of controls (C), brain injured patients who responded to therapy (R) and non-responders (N) when performing alone, and in combination with a range of auditory verbal secondary tasks. Tr denotes tracking only; +DF denotes tracking and digits forward; +DB denotes tracking and digits backwards; +TJ denotes tracking and temporal judgment; +Co denotes tracking and conversation; +VF denotes tracking and verbal feedback. Data from Alderman (in the press).

with an interpretation in terms of level of difficulty is the danger of circularity; unless there is some independent measure of difficulty level, then any differential impairment in AD patients can be attributed *post hoc* to hypothetical differences in underlying difficulty. The strength of the working memory model is that it attempts to specify sources of difficulty in a principled way. However, there clearly remains a need to understand the underlying process in more detail, and to contrast the effects of increasing the level of difficulty of a single task with that of requiring task combination.

Another basic question regarding the dual task technique concerns its generality of application. If it reflects a basis executive function, then one might expect dual task performance decrements to occur more widely than simply in DAT patients. Evidence is beginning to accumulate that this is indeed the case, with a study by Dalrymple-Alford (1994) showing significant though smaller dual task decrement in Parkinson's disease, while Hartman *et al.* (1992) observed a dual task decrement in patients suffering from traumatic brain injury, with a suggestion that the impairment may have been greater for subjects showing impaired performance on tasks typically associated with frontal lobe dysfunction. This study had the further aim of exploring the possible implications of dual task deficit on the process of rehabilitation, demonstrating that concurrent conversation, although not simple encouragement, had a detrimental effect on motor performance in brain damaged patients, while having no such effect on the performance of control subjects. They conclude that, while it may be appropriate for physiotherapists to chat to their patients while treating them, in the case of brain damaged patients this could be counter-productive.

Another potentially important clinical application of the dual task method is described by Alderman (1996), a clinical neuropsychologist operating within a programme attempting to assist brain damaged patients with severe behavioural problems. The programme is based on a token economy system whereby patients are rewarded for behaving in a socially acceptable way. In general, the programme is very effective in helping patients to deal with the anti-social behaviour that would otherwise prevent them participating in a rehabilitation programme. However, a small but important minority of patients failed to benefit from the regime; Alderman set himself the task of attempting to predict who these would be. He chose to test all incoming patients on a range of measures including both classic 'frontal' tests such as verbal fluency and the Wisconsin card sorting test, and also a range of variants of dual task performance. The behaviour of the subjects was subsequently monitored, and patients assigned to separate groups depending on whether they did or did not benefit from the rehabilitation regime. The results of the study are shown in figure 3, from which it is clear that whereas single task performance does not differentiate between the groups, subjects who do not thrive within the system tend to perform badly on a tracking task under dual task conditions. The differential decrement occurred whether the concurrent task involved digit span forward, digits backward, conversation or a task requiring judgment of how long specified activities such as travelling from London to Glasgow by train might take. As in the Hartman *et al.* (1992) study, when the secondary task involved only non-specific encouragement, all three groups showed a tendency for the tracking task to improve over the single task baseline. Of the four more traditional frontal lobe tests used (cognitive estimates, verbal fluency Wisconsin card-sorting and trails A and B), only trails B showed a clear inter-group difference, with the rest showing a small and marginally significant tendency to poorer performance in the non-responding group.

4. DUAL TASK PERFORMANCE AND FRONTAL LOBE FUNCTION

Preliminary evidence therefore suggests that the capacity for combining the performance of two tasks may be an executive process of some generality, and potentially of practical as well as theoretical significance. It appears to have a degree of overlap with more traditional measures of frontal lobe function, but with evidence from Alderman's study that it may allow better prediction of certain types of behavioural breakdown. The final study to be described is concerned with investigating the relationship between dual task performance and frontal lobe function and is based on a sample of patients selected on the basis of known frontal lesions (Baddeley *et al.* unpublished results).

A total of twenty-seven patients with radiologically verified lesions of the frontal lobes were assessed using the box crossing task combined with concurrent digit span. All subjects were also assessed on Nelson's shortened form of the Wisconsin card sorting test, and on letter fluency, being required to generate as many words as possible beginning with the letters F, P and L, each within a one-minute period. Finally, each patient was independently assessed by two neurologists on the basis of whether they showed behavioural disturbances of a type characteristically associated with the dysexecutive syndrome. One of the raters based the assessment on the patient's notes, while the other used comments by the patient's relatives, together with observed behaviour during testing as a basis for the classification. The estimates agreed for all but three patients who were subsequently discarded from the analysis, leaving two groups of patients, a dysexecutive and non-dysexecutive group both containing twelve subjects. The nature of the behavioural disturbance varied, with a slight preponderance of patients tending to show apathetic behaviour ($N = 7$), with four tending to be dysinhibited, and one oscillating between the two. These differences were not subsequently reflected in test performance.

Considering the combined group of 24 subjects with frontal lobe damage, there was a significant tendency for patients to score below the cut-off based on population norms for both the Wisconsin card sorting test (20 below cut-off) and on verbal fluency (17). When the two sub-groups were compared however, there was no significant difference in verbal fluency or card sorting performance between the group showing dysexecutive behaviour and those who appeared to behave normally, although there was a non-significant trend for poorer performance in dysexecutive patients.

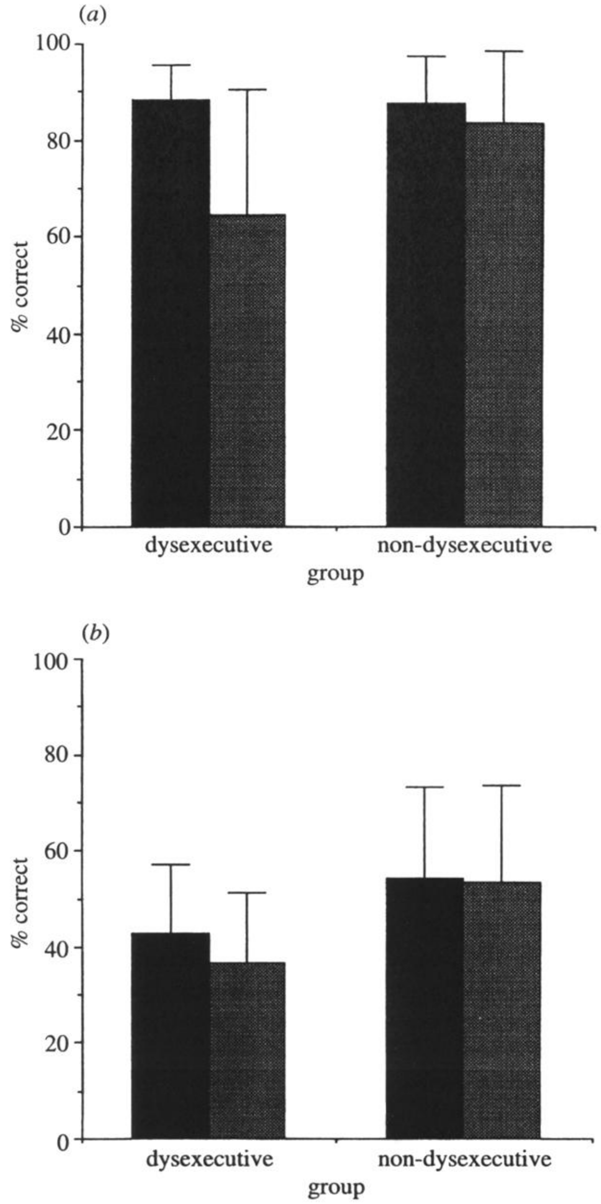

Figure 4. Effect of dual task on (*a*) memory span and (*b*) tracking performance in two groups of frontal lobe patients. Those patients showing dysexecutive behaviour were impaired on dual task performance while patients showing no behavioural disturbance showed no such decrement (data from Baddeley *et al.* 1996*b*). (Solid bars denote single task; hatch bars denote dual task.)

When performance of the two groups on dual task performance was compared, as figure 4 shows, there was a significant tendency for the dysexecutive group to show a decline in performance when the two tasks were combined, an effect that was significant for the memory score ($p < 0.02$), the combined task ($p < 0.02$), but not for the tracking score.

This study therefore reinforces the conclusions drawn from that of Alderman, in suggesting that dual task performance is a potentially useful marker of dysexecutive behaviour. The fact that it is found in half our sample of patients with frontal lobe damage clearly implicates the frontal lobes, while suggesting that by no means all patients with frontal lobe damage will show either dual task deficit or the characteristic behavioural

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disorder. It is interesting to contrast the pattern of dual task performance with those shown by the two more traditional frontal tasks, which appear to be clearly associated with frontal damage, but dysociable from dual task performance. As such, our findings are consistent with the view that both the frontal lobes and executive processes may be fractionable into subsystems, possibly with different anatomical locations, although our own results provide no direct evidence on this last point.

Our finding of a clear association between dual task performance and behavioural disorder was serendipitous, but in combination with Alderman's results are very encouraging. It is perhaps worth noting at this point that Shallice & Burgess (1991) have observed a sub-group of patients with frontal lobe damage who appear to be able to pass virtually all the standard tests, and yet are sufficiently disturbed in their social activities as to make it impossible for them to return to a structured occupation. One of the clearest predictors of this behavioural disturbance is the six elements test, in which subjects are required to perform a task comprising six parallel subtasks which must be performed in a coordinated manner in order to receive a high score. It seems plausible to assume that Shallice & Burgess's richer and more complex six task coordination measure may rely on a similar function to our dual task test.

5. FURTHER FRACTIONATION OF THE CENTRAL EXECUTIVE

We have so far confined our attention principally to one executive capacity, with what we regard as encouraging results. It is, however, clearly the case that any adequate model of the central executive must have a range of other sub-processes if it is to be capable of serving the role of attentional controller, organizer of learning and retrieval planner. We have therefore begun to apply the same logic to the postulation of further potentially separable executive processes (Baddeley 1996). One important function must be that of selective attention, the capacity to focus attention on one stream of information while shutting out irrelevant material. Another is presumably involved in the capacity to switch attention from one source to another, a process that we suggest may underlie the difficulty experienced in attempting to generate random sequences, where subjects become locked into retrieval patterns and tend to produce stereotyped responses under time pressure (Baddeley 1966). A very important executive demand on working memory is provided by the need to access and manipulate information in long-term memory. We suspect that it is this function of the central executive that plays an important role in individual difference measures of working memory span such as that developed by Daneman & Carpenter (1980). The processes of comprehending a complex prose passage also seem likely to make demands on the capacity of the central executive to set up and manipulate models within long-term memory, as recently proposed by Ericsson & Kintsch (1995). It seems unlikely that this list is exhaustive, and since we have very little understanding of most of the processes outlined, we clearly have a good way to go in understanding the functioning of the central executive.

There are obvious dangers in postulating an unlimited number of executive processes. Simply inventing new tasks on *a priori* principles and then nominating them as measures of basic executive processes is clearly not a satisfactory solution to the problem of analysing the central executive. It is necessary, first of all, to postulate only processes that have some chance of operating across a range of different materials and situations, and then to demonstrate this generality. In due course, when adequate measures of a number of supposedly different executive processes have been developed, it will be necessary to carry out larger scale correlational studies using patients who are likely to have a range of executive problems. If we have been successful in isolating a number of separable executive processes, then we would expect a higher correlation across different tasks that are assumed to measure the same process, with clear separation from other clusters of proposed executive processes. This leads on to the question of how the component sub-processes are related; we do not propose a multiplicity of executives, but wish to leave open to empirical investigation the question of whether the organization is hierarchical, with one or more subsystems dominating, or whether a more heterarchical structure is involved.

Another potential sources of validating data comes from studying the pattern of executive deficits across different subject populations who might be expected to have differential disruption of the functioning of the central executive. It seems likely that some executive processes for example, will deteriorate with normal aging. Our own data suggest this will not be true of all executive processes since the capacity for dual task performance appears to be preserved, provided the level of difficulty of the relevant tasks is matched across groups, whereas as we have seen, dual task performance appears to be an area of clear deficit in DAT patients.

Finally, a clearly formulated and well structured functional model will provide a much sounder basis for studies concerned with the anatomical localization of executive processes. While lesion studies have been, and will continue to be important, the rapid developments in neuroimaging are particularly promising. Working memory has already proved a fruitful area for PET studies with models initially based on studies within cognitive psychology showing very good correspondence with neuroanatomical distinctions based on functional imaging. The fruitfulness of this approach has already been established in studies of the phonological loop (Paulesu *et al.* 1993) and the visuo-spatial sketchpad (Jonides *et al.* 1993). Work has now begun to appear on the functional imaging of dual task performance (D'Esposito *et al.* 1995), suggesting, we are happy to note, a frontal lobe involvement. Recent studies of learning suggest the possibility that the executive processes involved in organizing and encoding incoming material may have a left frontal location, whereas those involved in episodic retrieval seem to be mediated by areas in the right frontal cortex (Shallice *et al.* 1994; Tulving *et al.* 1996). Conclusions in this area are still preliminary, but if established, these latter findings may represent a new stage in the application of functional imagery to the analysis of cognitive function. The pattern so far has been one of establishing the viability of the imaging method by demonstrating that it is capable of giving clear and replicable anatomical answers to the location of functions that have typically already been specified and broadly localised on the basis of cognitive and earlier lesion studies. Having established its viability, functional imaging is now in a position to suggest hypotheses which will enrich and may well change our functional models of cognition.

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Discussion

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In the experiments using the dual task paradigm, in patients

with Alzheimer's disease, what proportion of the patients were impaired relative to controls in the single tasks, before matching for performance? If performance between patients and controls is significantly different what implications, if any, are there for interpreting the nature of the dual task decrement?

A. BADDELEY. While neither digit span nor tracking are especially sensitive to the effects of AD, there is a consistent tendency for poorer performance in patients than controls (Spinnler *et al.* 1988), hence the need to titrate the level of difficulty of each task so as to equate performance on patient and control groups. The adjustment of performance is based on the assumption that subjects who are performing at a similar error rate, selected to avoid floor and ceiling effects, will be operating at a broadly equivalent level of cognitive demand. While this seems a plausible assumption, we do not currently have good measures to test its validity. However, while the optimal method of equating difficulty across groups remains open to question, there is no doubt that failure to do so would lead to a spuriously large effect of combining tasks in the AD group.

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