Complexity and Working Memory Resources: Task Characteristics Necessitating the Executive Control of Attention[1]

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A b s t r a c t

The executive functions of human working memory have recently become a common target of investigation, mainly in neuroimaging and patient studies. Those studies have indicated that executive functions are (a) strongly related to the functions of the prefrontal structures, and (b) are required whenever the task reaches a certain level of complexity. However, numerous attempts to operationally define that level of task complexity have resulted in different, and sometimes contradictory hypotheses as to what specific task characteristics necessitate executive control over attentional resources. The experiment reported here attempts to address that issue from a behavioural perspective. A dual task was used and task characteristics which have previously been shown to be of importance in defining task complexity, were varied independently of each other. Several previous neuroimaging and patient studies were used to predict a specific pattern of interference between the two tasks, depending on whether the activation of overlapping brain regions should be expected. Two points are relevant in discussing the results. First, methodologically, they show that neuroimaging results can be successfully used to generate behavioural predictions. Second, conceptually, the results show that one of the previously proposed task complexity features - the need to carry out multiple processing operations simultaneously - is not sufficient by itself to necessitate executive processes. It is suggested that a task characteristic predictive of executive resources involvement, is the need for *alternating between different processes* (or schemas) during behaviour - a mechanism which was originally proposed to underlie the executive control over attentional resources (Norman and Shallice, 1986).

Keywords: working memory; executive functions; dorsolateral prefrontal cortex; task complexity; multi-attribute stimulus evaluation; dual tasking.

Introduction

The term *working memory* is commonly used to denote the various supplementary processes that need to be carried out while performing some complex cognitive task. In order to be able to comprehend a narrative, devise a plan, or solve a problem, we need some means of handling the relevant information - keeping it active in memory and transforming it - and working memory is postulated to be the system supplying those means. As it is easy to see, in its role as such, it becomes an important contributor to the end result of the task being performed as the outcome of performance is determined by the efficiency with which this information is handled. Maybe because of this critical stand in cognitive processes, working memory has not only received a wide popularity and attention among researchers in different areas, but it has occasionally even come to be equated with the cognitive processes that it is presumed to subserve (for instance, Kyllonen and Christal, 1990).

The concept of working memory was originally introduced as the main function of the short-term memory system (as proposed by Atkinson and Shiffrin, 1968), but it later evolved into a concept of separate memory system in itself. The Working Memory system was introduced by Baddeley and his colleagues (Baddeley and Hitch, 1974) and has increasingly replaced (Growder, 1982) the older concept of short-term memory to an extent that now they are often used interchangeably.

Generally, working memory has been specified (for instance, Baddeley, 1992a) as a tripartite system, including an attentional controller, the *central executive*, that is aided by two slave systems, the *visuospatial sketchpad*, which has the function of holding and manipulating visual and spatial images, and the *phonological loop*, which involves a speech-based system. In this form, the working memory model has proved to be a useful theoretical construct not only in explaining results from behavioural experiments but also in providing an experimental framework for different neuroimaging and neuropsychological studies.

While behavioural studies have aimed at identifying the functions and properties of these three subsystems, research in the neuroscience area has attempted to identify them in terms of brain structures. THE PHONOLOGICAL LOOP is perhaps the most extensively studied of the three components. Behavioural studies have establishes two main functions of the phonological loop (Baddeley, 1992b) - (a) maintaining phonological information by subvocal rehearsal, and (b) transforming visually presented material, such as words or identifiable pictures into some phonological code, and again maintaining it by subvocalization. Neuroimaging studies have identified the phonological loop in terms of brain regions, known to be related to speech and phonological processing. Areas that are known to be invariably activated when phonological retention of

material is required are Broca's area (left inferior frontal gyrus or BA 44), as well as the premotor cortex and the supplementary motor area (BA 6). These three regions have all been shown to be involved in articulatory coding and motor output during language production (Peterson, Fox, Posner, Mintum, and Raichle, 1988). Also, Paulesu, Frith, and Frackowiak (1993) reported activation in Broca's area as well as in temporal (BA 22 and 42) and parietal lobes (BA 40) when participants were performing a task requiring brief retention of phonological information. Again, activation in Broca's area as well as in left parietal regions (BA 40) were observed by Awh, Jonides, Smith, Schumacher, Koeppe, and Katz (1996) using Saul Sternberg's short-term memory task (Sternberg, 1966), a specific type of memory-span task.

Similarly, the second 'slave' system, THE VISUO-SPATIAL SKETCHPAD, has been studied in both the behavioural and neuroscience areas. The characteristics of the visuo-spatial sketchpad have been found to be analogous to those of the phonological loop (Baddeley, 1990). Like the loop, information can be fed either directly, in this case through presentation of visuo-spatial information, or indirectly, through presenting for instance auditory material which is being transformed into a visual code and then maintained within the sketchpad. Activation in right-hemisphere brain regions have been demonstrated for spatial working memory task (e.g. Jonides, Smith, Koeppe, Awh, Minishima, and Mintum, 1993), with the areas being roughly analogous to those found activated for verbal working memory tasks in the left hemisphere.

The attempts to study THE CENTRAL EXECUTIVE component of working memory have resulted in somewhat more controversial evidence as to its functions and associated brain regions. On the behavioural side it was largely neglected, partly because the slave systems provided an easier target for experimentation and partly because there were no previously established experimental paradigms, which could be adapted to studying its properties. As it was theoretically assumed (Baddeley, 1992b), its functions were that of an attentional control system responsible for strategy selection and planning, as well as integration of information from the two slave systems. It is considered to be involved during the performance of complex cognitive tasks, such as problem solving, which generally require the generation of strategy for handling the necessary information, in addition to maintaining and manipulating it.

More recently, the central executive has begun to be specified in bigger detail, in terms of the Norman and Shallice (1980) Supervisory Attentional System. Norman and Shallice proposed their model in an attempt to account for the properties of the attentional (or willed) control of action. The model assumes that behaviour consists of the successive execution of schemas, relevant to the specific situation in which the behaviour is required. A schema is selected for execution if its activation level exceeds a certain threshold. As experience with certain tasks increases, the particular schemas controlling them become more specific to those tasks and are automatically activated in the succession that they need to be executed. However, when a task is novel or complex, numerous schemas can be simultaneously activated above threshold, and some additional selection mechanism is required to determine which one of them to execute next. The Supervisory Attentional System (SAS) is assumed to provide this mechanism for additional control over action. It achieves that by applying extra activation and inhibition to schemas and thus biasing their execution. A characteristic property of the SAS is that it is responsible for the deliberate conscious control of behaviour, and is distinct from the mechanisms used in automatic actions.

The functions of the SAS correspond closely to the functions ascribed to the prefrontal cortex. Various neuropsychological studies suggest that the prefrontal areas are involved in tasks requiring deliberate attention to behaviour. Lesions confined to prefrontal structures leave the execution of routine skills such as the use of objects, speaking, and writing unaffected (Walsh, 1978). For instance, performance of the Wechsler Adult Intelligence Scale test is relatively unaffected by frontal lobe lesions (McFie, 1960). However, when a task requires some form of planning, regulation or monitoring of current activity, frontal patients show characteristic deficits in performance. Thus, Shallice (1982) has shown that patients with frontal lesions are significantly more impaired than those with lesion in other sites in look-ahead puzzles related to the Tower-of-Hanoi task; comparison of performance on this task with that on other tasks suggested that it was the planning component of the task that was affected.

Except for planning, executive control seems to be involved whenever a task requires some form of shift in strategy. For instance, the Wisconsin card-sorting test involves multidimensional stimuli and requires the patient to switch from sorting on one dimension to sorting according to another. In this task, frontal patients show a strong tendency to perseverate in sorting on the previously correct dimension, even if they are told they are wrong (Milner, 1982; Nelson, 1976).

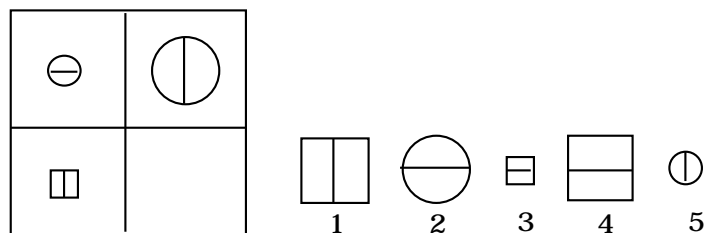Other well-known examples of tasks involving consideration of multidimensional

Figure 1. Typical matrix item varying along multiple spatial dimensions (example taken from the Cattel Culture Fair test).

Brodmann's Area

stimuli are the Cattel's Culture Fair test[*] and the Raven's Progressive Matrices test (Raven, 1965). The two tests include different spatial problem items, presented in a matrix form. A typical matrix item is shown in Figure 1. The different figures included in a matrix item vary systematically in shape, size, or some other dimension. The task is to decide which of the choice alternatives correctly completes the matrix, and in order to be solved, all variations along the different dimensions have to be considered.

Frontal patients have been found to be impaired on both of those multi-dimensional matrix tests. Thus, a study by Duncan, Burgess, and Emslie (1995) revealed substantial deficits in performance on the Cattel's Culture Fair test. Another study, using the Raven's Progressive Matrices test (Waltz, Knowlton, Holyoak, Boone, Mishkin, de Menezes Santos, Thomas, and Miller, in press) found the same pattern of results, but even more specifically, it was shown that prefrontal patients were impaired on two-dimensional items (*two-relational* problems in the authors' terms), whereas their performance on the one-dimensional items (or *one-relational* problems) was at a control level.

Recent neuroimaging studies have provided additional evidence that prefrontal structures are involved in tasks requiring executive control of attention. The Tower-of-London, a task which involves planning and which reveals deficits in frontal patients, was found to produce activation in the dorsolateral and rostral regions of the prefrontal cortex in several studies (Baker, Rogers, Owen, Frith, Dolan, Frackowiak, and Robbins, 1996; Morris, Ahmed, Syed, and Toone, 1993; Owen, Doyon, Petrides, and Evans, 1996).

Using a dual task, a paradigm in which two tasks have to be performed concurrently, D'Esposito, Detre, Alsop, Shin, Atlas, and Grossman (1995) found activation in the dorsolateral prefrontal cortex (BA 9 and 46). The tasks used in this study were one verbal and one spatial task, and the participants performed them either singly or simultaneously. Since the activation in the dorsolateral prefrontal cortex (DLPFC) was specific to performing the two tasks simultaneously, and did not appear during performance of either one of the tasks alone, D'Esposito *et al*. concluded that the DLPFC was involved in the processes specific to dual task performance - such as control and allocation of attentional resources between the two tasks.

Other neuroimaging studies have used tasks involving stimulus variation across different dimension, a type of manipulation which was previously mentioned as sensitive to prefrontal lesions. For instance, Corbetta, Miesin, Dobmeyer, Shulman, and Petersen (1991) used a spatial same-different matching task, in which different visual attributes of the stimuli were varied (shape, color, and speed) and participants had to detect a change in one of the attributes. When this attribute was predetermined, and was therefore selectively attended to, the DLPFC did not seem to be activated. However, when a change in an arbitrarily selected attribute had to be detected, and therefore a deliberate attentional shift among the different attributes was required, the DLPFC showed a significant amount of activation. Similarly, Prabhakaran, Smith, Desmond, Glover, and Gabrieli (1997) reported activation of the same prefrontal region during performance of the Raven's Progressive Matrices test. The problem items used in this study varied along two dimensions, and consideration of changes on both dimensions was required for solving them. The brain activation results, pertaining to activation of the frontal areas, are shown on Figure 2b.

DLPFC activation was also shown for tasks that require the simultaneous (or alternating) storage and processing of information, such as *the n-back task* (Mackworth, 1959). During an n-back task, participants are presented with a series of items, each appearing one at a time, followed by the next item in the series. The task is to press a button when the item that is being presented at the moment is the same as the one presented a certain number (*n*) of items earlier. For instance in a one-back task, the button has to be pressed if the item is the same as the one presented immediately prior to it, whereas in a two-back task, it has to match the item presented *before* the last previously presented item, and so on. With increase in the number of items that have to be searched back (or *n*), the number of previously presented stimuli that has to be maintained while encoding each new stimulus increases as well. Thus, the n-back task allows to parametrically vary the concurrent working memory load: by increasing *n*, the concurrent load increases as well. Results from different neuroimaging studies show increased DLPFC activation when the concurrent maintenance requirements are increased in this way (Cohen, Forman, Braver, Casey, Servan-Schreiber, and Noll, 1994; Cohen, Perlstein, Braver, Nystrom, Noll, Jonides, Smith, 1997; Petrides, Alivisatos, Meyer, and Evans, 1993; Smith, Jonides, and Koeppe, 1996).

However, it should be noted that in this case, the DLPFC activation can be attributed, at least in part, to the maintenance component of the task. Even thought the n-back task does require that multiple processing operations be carried out, thus necessitating executive control of attentional resources, there still remains the possibility that this part of the prefrontal cortex is involved in maintenance *per se*.

Indeed, two recent studies (Manoach, Schlaug, Siewert, Darby, Bly, Benfield, Edelman, and Warach, 1997; and Rypma, Prabhakaran, Desmond, Glover, and Gabrieli, in press) found DLPFC activation even when a simple verbal maintenance task is performed, although in this case there is no apparent need to alternate between different processing operations. Both studies used the Sternberg Item Recognition Paradigm (Sternberg, 1966). The task consists of presenting participants with a number of letters, some of which (but not necessarily all) are marked to show that they have to be remembered for later recognition. After a brief retention period, a single probe letter is presented and the participants have to press a button if the probe was

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[*] Institute for Personality and Ability Testing. *Measuring Intelligence with the Culture Fair Tests.* The Institute for Personality and Ability Testing, Champaign, IL, 1973.

marked as a to-be-remembered item among the previously presented set of letters. In the study by Rypma *et al.* there were three levels of memory load - the number of items that were marked as to-be-remembered was either *one*, *three*, or *six*. The brain activation results can be seen on Figure 2a. In this study, the three-item memory load, when compared to the one-item memory load, revealed activation in Broca's area (BA 44) and no DLPFC activation was found. However, when the six-item memory load was compared to the three-item load, except for Broca's area, additional activation occurred bilaterally in several prefrontal regions, and perhaps most notably, there was a bilateral DLPFC activation (BA 46 and 9). Those results provide strong evidence that this part of the prefrontal cortex is involved in tasks that require concurrent maintenance of increased amount of information, even when that maintenance is the only processing operation that needs to be carried out in order for that task to be solved.

In short, *tasks which have been found to require the dorsolateral regions of the prefrontal cortex, seem to possess some of the following characteristics: (1) the stimulus material needs to be analyzed along different dimensions; (2) multiple processing operations have to be carried out simultaneously during performance (dual tasks); (3) the working memory load that needs to be maintained exceeds a certain number of items.*

However, the question as to whether each of those task characteristics by itself is sufficient to activate this region of the prefrontal cortex still remains open. Studies that have varied one of those parameters have usually involved variation along some of the other parameters too, and it is therefore not clear whether the three characteristics outlined above can be considered to necessitate executive resources independently of each other. For instance, in the study by Cohen *et al.* (1997), the working memory load was varied through increased number of letters to be searched back in the n-back task. However, as that number is increased, the number of cognitive operations that have to be carried out simultaneously is increased too. The study by D'Esposito *et al.* (1995) varied the number of simultaneously performed operations by comparing a dual task to a single task conditions, but it is possible that simultaneously with that the working memory load was increased considerably too, thus the number of items to be held in working memory exceeding the critical number in the dual task condition. Similarly, Corbetta *et al.* (1991) varied that number of dimensions (or attributes) along which the stimulus had to be evaluated, increasing it from one to three attributes. However, simultaneously with that the working memory load was varied too, through increased number of attributes to be held in working memory, thus possibly surpassing the critical number of items.
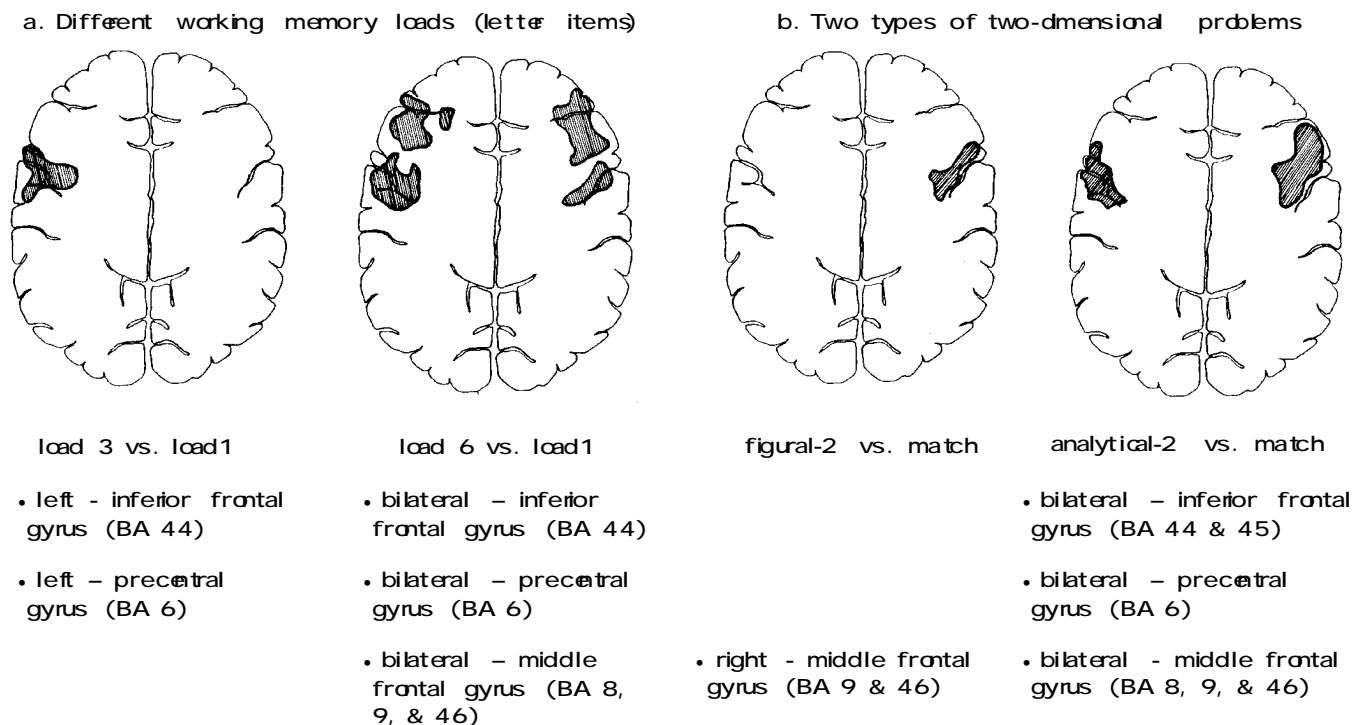
a. Different working memory loads (letter items)   **b. Two types of two-dimensional problems**

load 3 vs. load1   load 6 vs. load1   figural-2 vs. match   analytical-2 vs. match

- left - inferior frontal gyrus (BA 44)
- left – precentral gyrus (BA 6)

- bilateral – inferior frontal gyrus (BA 44)
- bilateral – precentral gyrus (BA 6)
- bilateral – middle frontal gyrus (BA 8, 9, & 46)

- right - middle frontal gyrus (BA 9 & 46)

- bilateral – inferior frontal gyrus (BA 44 & 45)
- bilateral – precentral gyrus (BA 6)
- bilateral - middle frontal gyrus (BA 8, 9, & 46)

Figure 2. Brain activation results from a) Rypma et al.'s (in press) study, using different number of letters to vary working memory load; and b) Prabhakaran et al.'s (1997) study, using two different type of problems, requiring two-dimensional stimulus evaluation. Axial view of the brain.

Undoubtedly, there are difficulties in establishing, and therefore controlling for this "critical" number of items, at or above which executive resources seem to be required. The main difficulty arises from the fact that for different items that critical number may be different. Thus, for letters and digits, it may be five or six, as the studies by Manoach *et al.* (1997) and Rypma *et al.* (in press) suggest. On the other hand, for items such as stimulus attributes, the critical number may be three, as suggested by the results reported by Corbetta *et al.*

(1991). However, if that critical number for certain type of items is established in previous studies, it can be used to control for working memory load while varying some of the other task characteristics. This was the approach undertaken in the experiment described below. Using the neuroimaging results from Rypma *et al.*'s study, the number of items to be held in working memory was controlled for being either *below* or *above* the critical level, as defined by the absence or presence of DLPFC (BA 9 and 46) activation correspondingly. The experiment attempted to establish whether the need to perform multiple cognitive operations simultaneously - the second task characteristic listed above - would require executive resources when the working memory load does *not* exceed the critical number of items. In other words, the main questions which the experiment tried to answer was whether this task characteristic by itself is sufficient to necessitate executive resources.

Experiment

Two different working memory tasks were combined in a dual task procedure. The first task used was a spatial reasoning task, including the earlier items from the Raven's Progressive Matrices (RPM) test. The second task was the Sternberg memory task, which was used to vary the working memory load that had to be maintained during performance. The memory load was varied at three levels - three items (3-load), six items (6-load), and no-load condition.

The brain areas involved in performance of the two tasks separately, have been outlined in previous neuroimaging and patient studies. Thus, based on the results from the study by Rypma *et al.*, the 3-load condition of the Sternberg memory task can be expected to activate Broca's area, but not DLPFC regions (see Figure 2a). In contrast, the 6-load condition would be expected to activate bilateral DLPFC regions, in addition to Broca's area. For the no-load condition, it could be expected that only a limited activation in Broca's area would occur, as a result of the overt articulation requirement, but it would be significantly lower than the amount of activation during the 3-load condition.

Table 2. **Expected profile of performance for the different problem types with variation of the working memory load. The expectations are relative to a base-line performance for each problem type, and are formulated on the basis of presence or absence of expected increased overlap in the activated brain areas as the working memory load increased.**

TYPE OF PROBLEM		WORKING MEMORY LOAD		
		Load 0 minimal activation in left inferior frontal gyrus (left BA 44)	**Load 3** increased activation in left inferior frontal gyrus (+ left BA 44)	**Load 6** increased DLPFC activation bilaterally (+ left and right BA 9 and 46)
TWO - DIMENSIONAL **Figural-2**	activation in right DLPFC (right BA 9 & 46)	*base-line* performance A	*base-line* performance A (no increased overlap in activated brain areas)	*decrement* in performance from base-line A (increased overlap in right DLPFC)
Analytical-2	bilateral activation in inferior frontal gyrus and DLPFC (left and right BA 44, 45, 9, & 46)	*base-line* performance B	*decrement* in performance from base-line B (increased overlap in Broca's area)	*further decrement in* performance from base-line B (increased overlap in DLPFC bilaterally)
ONE - DIMENSIONAL	no prefrontal areas involved	*base-line* performance C	*base-line* performance C (no increased overlap in activated brain areas)	*base-line* performance C (no increased overlap in activated brain areas)

The reasoning task, too, can be comparatively well characterized in terms of the brain areas required for its performance. Four different types of problems were used, and each of those types was classified as requiring consideration of either one or two dimensions of stimulus change. Based on the neuropatient studies by Duncan *et al.,* and Waltz *et al.*, it could be expected that the problems involving only one-dimensional stimulus change, would not require prefrontal brain structures. In contrast, the problems which involve consideration of stimulus properties along two dimensions, could be expected to require the activation of dorsolateral prefrontal areas. In addition, the problems that require stimulus consideration along two dimensions were shown in the neuroimaging study by Prabhakaran *et al.* to require DLPFC activation. This study also shows that the two-dimensional problems should be divided further into two categories, each characterized by a different pattern of DLPFC areas activation (see Figure 2b). Those problems that are

characterized by *visual* rules (as classified by Carpenter, Just, and Shell, 1990) can be expected to activate right DLPFC areas but would not require Broca's area activation. On the other hand, problems characterized by *analytical* rules, could be expected to activate both Broca's area and the DLPFC bilaterally.

A different profile of performance for each problem type of the reasoning task was expected as the concurrent memory load is increased from 0 to 3 and from 3 to 6. The expectations are outlined in Table 1. Varying of the working memory load served a twofold purpose. *First,* as the load was increased from 0 to 3, the number of simultaneously performed operations was increased too. However, on the basis of the previously described neuroimaging data, the 3-load condition was assumed *not* to exceed the critical number of items. Therefore, comparing performance in the 3-load condition to that in the no-load condition was expected to provide evidence as to whether simultaneously performing multiple cognitive operations (reasoning *and* holding letters in working memory) requires executive resources. For the two-dimensional problems, which alone are known to require executive processes (again, as defined by activation in the DLPFC areas), a decrement in performance would suggest that additional executive resources are required as the number of simultaneous operations is increased, independently of working memory load (without exceeding the critical number of items). It should be noted that only in the case of the figural-2 types of problems a decrement in performance from the no-load to the 3-load condition can properly be treated as indicative of increased need for executive resources. Here the decrement would be ascribed to increased overlap in activation in the DLPFC areas (see Table 1), which in the present paper is assumed to be also indicative of increased need for executive resources. However, for the analytical-2 type of problems, the same decrement in performance could not be treated as stemming from increased need for executive resources. In this case another reason for decrease in performance is more feasible in view of the imaging results - the increased overlap in activation of Broca's area (an area separate from the DLPFC regions).

Second, the 6-load condition compared to the 3-load condition does not require increase in the number of simultaneously carried out cognitive operations. However, the working memory load here exceeds the critical number of items. Therefore, a decrement in performance for the 6-load condition would suggest that exceeding the critical number of items in working memory by itself requires executive resources. For the one-dimensional problems no increased overlap in brain areas was expected as the working memory load is varied. Since those problems could be considered not to require executive resources for their performance, it was not possible to make inferences as to possible competition for such resources on the basis of the reasoning task performance measures. Those problems were included in the study for control purposes and as a possible way to provide further evidence that there are is no need for executive control of attention when a stimulus has to be evaluated only along one dimension.

Method

Design. The experiment had a within-subject design. There were two independent variables - memory load and problem type. The memory load was varied at three levels - a load of six letters (the 6-load condition), a load of 3 letters (the 3-load condition), and no concurrent memory load (the no-load condition).

There were four problem types for the reasoning task. First, half of the problems were *figural* and the other half - *analytical* type of problems. Second, both the figural and the analytical problems were either *one-dimensional* (varying only along one dimension) or *two-dimensional* (varying along two dimensions). Thus, the following four types of problems were used: figural-1 (one-dimensional figural type), figural-2 (two-dimensional figural type), analytical-1 (one-dimensional analytical type), and analytical-2 (two-dimensional analytical type).

There were forty-eight problems and each of them, in combination with the corresponding letters for the memory task, formed the forty-eight trials of the experiment. There were twelve problems for each of the problem types. All problems were arranged in a pseudo-random order, in blocks of twelve, with each problem type appearing three times in each block.

For the memory task, forty-eight sets of six letters were formed and each of those sets was randomly assigned to one of the problem items, with the restriction that none of the letters appeared twice together with two consecutive problem items. The so formed forty-eight experimental trials were presented in the same order to all participants.

From the forty-eight six-letter sets, sixteen appeared in the 6-load condition, sixteen - in the 3-load condition, and sixteen were replaced by a "recite alphabet" sign. The different memory load conditions were presented pseudo-randomly, in blocks of six, with each condition appearing twice in each of the blocks. The order of presentation of the memory load conditions in each block was randomized across subjects using Latin Square design.

There were twelve experimental conditions altogether (3 memory loads x 4 problem types) and each participant solved four problems in each of the experimental conditions. The accuracy (proportion correct) on the four problems in each experimental condition was the primary dependent measure. It was expected that the concurrent memory load would interact with problem type, producing different profiles of accuracy in the different problem types. More specifically, it was expected that

   a) accuracy on the figural-2 problems would not differ between the no-load and the 3-load conditions, but will decrease for the 6-load condition;

   b) accuracy on the analytical-2 problems will decrease from the no-load to 3-load, and would decrease further from 3-load to 6-load condition;

   c) accuracy on the figural-1 and analytical-1 problems would not differ between the different memory load conditions.

Participants. Twenty-one Stanford University undergraduate students took part in the experiment. From them, nine (43 percent) were female. Age ranged between 18 and 22 years, with a mean of 19.5 and a mode of 20. All participants received credit toward their introductory psychology course.

Materials. The letters for the memory task, as well as the items for the reasoning task, were presented on a computer monitor. For the reasoning task, the different problem items were either original items from the Raven's Progressive Matrices Set or similar ones created for the purposes of the experiment so that the formal structure of the RPM problems was preserved. Each item consisted of a 3x3 figure matrix, with the bottom right figure missing, but logically following from the other eight presented figures (see Figure 3). In addition to the 3x3 matrix, four choice figures were presented and the task consists of choosing one of them as the missing figure.

a.   Figural-1
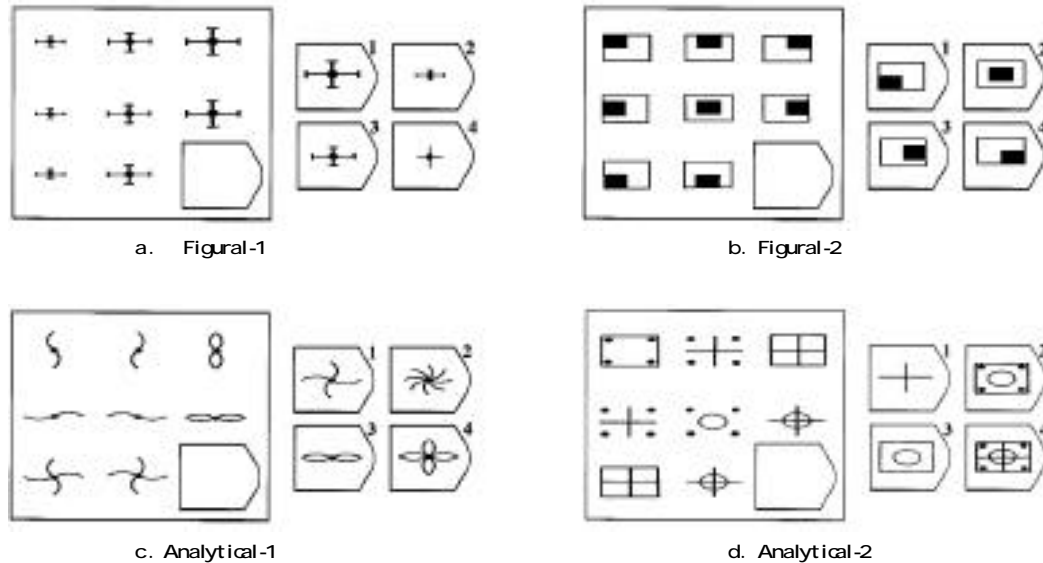
b.   Figural-2

c.   Analytical-1

d.   Analytical-2

Figure 3. Examples of different problem types used for the reasoning task.

The figural-1 type of problems were characterized by a quantitative progression along one dimension (the horizontal in Figure 3a) and no change of the figure in the other direction. Thus, in order to induce the rule according to which the figures changed, only one relation between figures had to be considered at a time. In contrast, the figural-2 type of problems were characterized by a pairwise progression along both dimensions, horizontal and vertical, so that the rule according to which the missing figure had to be chosen included consideration of both the horizontal and vertical dimension of attribute change.

The analytical type of problems were characterized by figure addition or figure subtraction. For those problems, two figures (or separate parts of them) in the same row or column have to be either superimposed or subtracted in order to produce the third one. In the analytical-1 type, the rule could be applied to the whole figure. For instance, in the example on Figure 3c, the first two figures in each row or column are superimposed (or added) in order to form the third. Thus, like in the figural-1 type of problems, in order to decide which is the missing figure it was sufficient to consider the change along one attribute. In the analytical-2 type, the different rules could apply to different parts of the figures. In the example on Figure 3d, after decomposing the figures into their parts, it could be seen that in order to produce the third figure, the dots should be subtracted whereas the rest of the elements should be simply added. Thus, inducing the rule for producing the third figure requires consideration of figure attributes change along two dimensions.

Both types of figural problems could be solved by a predominantly visual strategy since the rule from which the missing figure followed was based on some visual increment or decrement in the figures. The analytical problems on the other hand, required decomposition of the constituent elements of the figures and further analysis of the rules according to which those elements changed. Thus, the required strategy here involved was more analytical than the strategy for the figural problems.

The Sternberg memory task was used as a secondary verbal working memory task. The six letters were presented simultaneously, as shown in Figure 4. For the 6-load condition, all six letters were surrounded by parentheses. For th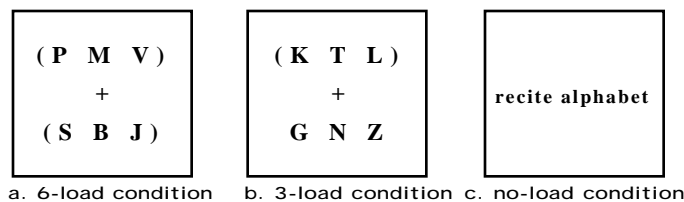e 3-load condition, only three of the letters were in parentheses (either the upper or the lower row, with equal probability). All of the letters were upper-case consonant letters. The six letters within each memory item were chosen so that they do not form a meaningful combination and are not arranged in a consecutive alphabetical order.

a. 6-load condition   b. 3-load condition   c. no-load condition

Figure 4. Examples of stimuli used in the different memory load conditions.

For the no-load condition, there were no letters to be remembered. Instead, the instruction to recite alphabet appeared.

The probes to the memory task consisted of a single letter, presented in the middle of the screen. The probe letter was a lower case letter, in order to avoid a pure visual-matching strategy of matching the probe item with the previously presented items. In the no-load condition, instead of probe letter, the first three letters of the alphabet appeared on the screen ("abc").

Procedure. Immediately prior to the experiment, participants were given a 10-min practice session, during which they practiced rehearsing at a constant speed of three letters per second and were given a chance to practice performing both tasks simultaneously, until they felt comfortable with the procedure. The experiment began by a sentence on the computer monitor, instructing the participant to press any key when ready. When a key was pressed, a brief fixation mark was presented in the center of the screen, followed immediately by presentation of the Sternberg working memory task. The letters for the Sternberg memory task stayed on the screen for either 4.5 sec (for the 6-load condition) or 2.5 sec (for the 3-load and no-load conditions) and were immediately followed by presentation of a Raven's problem item. Participants had to rehearse aloud the letters marked by parentheses (or the letters "a b c" in the no-load condition) exactly twice for the time period of their presentations. This duration, allowing for 0.5 sec of encoding, required that the speed of rehearsal be three letters per second in each of the experimental conditions. Participants were instructed to use this time duration as feedback as to whether they were rehearsing at the appropriate speed. This was done to ensure that the rate of rehearsal stays the same among the different problem items. Overt rehearsal was required in all memory load conditions to ensure continuous maintenance of the required number of items throughout performance of the reasoning task. For the no-load condition, participants had to simply rehearse aloud a prelearned sequence of letters (the first three letters of the alphabet). The last requirement was needed in order to equate for motor articulatory requirements in all memory load conditions.

The articulation rate was monitored by the experimenter and participants were prompted if they failed to maintain a consistent rate of rehearsal. They were instructed that they should not slow down their rehearsal rate while solving and this was emphasized during the practice session.

They had to press one of four keys, marked [1], [2], [3], or [4] on the computer keyboard, according to the number of the answer they had chosen as correct. Immediately after their answer on the reasoning problem, a letter probe appeared on the screen, to which they had to press a "YES" or a "NO" button, depending on whether it had been among the letters that had to be remembered in this trial. The YES and NO buttons were again two keys on the computer keyboard, labelled correspondingly. Their answer to the letter probe marked the end of the trial and was followed by the intertrial interval and the sign "Press any key when ready." appearing again on the screen. Participants were told that their answer on the reasoning task was of primary importance, but remembering the letters was important too, and that their answer on the reasoning task would not be considered correct unless they had answered the letter probe for the item correctly.

Results

Accuracy and latency of response for the reasoning task were recorded, as well as accuracy on the memory probe. The reasoning task accuracy was the primary dependent measure and it was defined as the percentage of correct answers for the four problems in each experimental condition.

However, in order for a Raven's problem answer to be considered correct, the response to the memory probe associated with this problem had to be correct as well. This correction was needed to assure that the participant had performed both the reasoning and the memory task in each trial. In general, the memory probe response accuracy was very high, and mistakes were made on 4.05% of the trials for the non-zero memory load conditions. The memory probe accuracy for each experimental condition is shown in Table 2. It did not differ significantly between the 3-load and 6-load conditions, as shown by paired t-test comparisons carried out separately for each of the four different problem types (t < 2.00, d.f. = 21, p > 0.05 on all four tests).

In addition, solution latencies for the reasoning problems were analyzed. Response times which were more than two standard deviations away from the mean for each experimental condition were considered outliers and correct answers on the reasoning task in such cases were discarded. On the average, 5.3% of the responses were found to be outliers. The response time measures for each experimental condition are shown in Table 2. Within each type of problem, the percent outliers for the different memory loads were subjected to a one-way analysis of variance. For the different problem types, the percent of outliers did not differ between the different memory load conditions, as shown by one-way analyses of variance carried out for each problem type (F[2,63] < 0.7, p > 0.6 on all four tests). Also, none of the differences was significant by Newman-Keuls tests.

The percentage of accurate responses for the reasoning task was subjected to a 3 x 4 analysis of variance (memory load vs. problem type) which yielded significant main effects of memory load (F[2, 240] = 4.365, p < 0.02) and type of problem (F[3, 240] = 43.001, p < 0.001). The analysis for the effect of load on each separate type of problem is given below.

Two-dimensional problems. Mean accuracy as a function of memory load and problem type (figural-2 and analytical-2) is shown in Figure 5. The effect of memory load for each problem type was analyzed using planned orthogonal comparisons. For the figural-2 problem type, the contrasts were (a) 3-load vs. no-load condition and (b) 6-load vs. lower load conditions. The 3-load condition did not differ significantly from the no-load condition (t = 0.176, d.f. = 60, p > 0.4, one-tailed), whereas the 6-load condition was found to be significantly lower in comparison with the other two memory loads (t = 2.139, d.f. = 60, p < 0.02, one-tailed).

Since the analytical-2 problems were the most difficult problem type, it was possible that some participants had been at a chance level in all of the different memory loads. The expected decrement in performance between the different memory load conditions could not be observed in this case. To eliminate such possibility, individual performance for the different memory loads was examined. Three of the participants

were found to be at chance level in every memory load condition. Those participants were removed from further analysis for this problem type.

A planned linear contrast between the different memory load conditions showed a significant linear trend in the predicted direction ($t = 1.815$, d.f. = 51, $p < 0.05$, one-tailed). Two additional comparisons were performed to examine the differences between successive memory loads. Each of those comparisons approached significance ($t = 1.51$, d.f. = 51, $p < 0.07$ for the no-load vs. higher loads contrast and $t = 1.63$, d.f. = 51, $p < 0.06$ for the 6-load vs. lower loads contrast).

Figure 5. Mean accuracy on the reasoning task according to memory load and problem type for the two-dimensional problems.
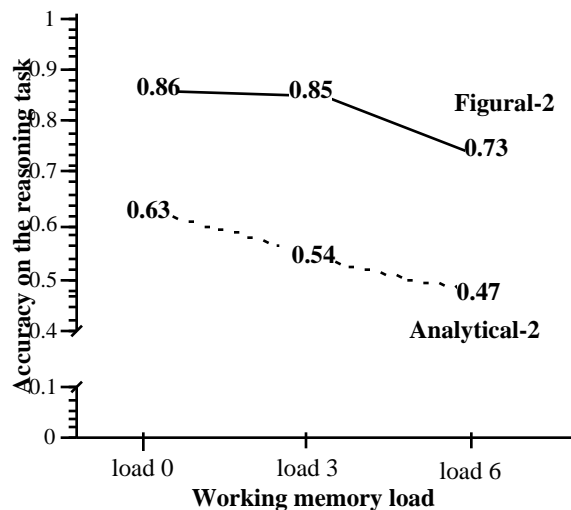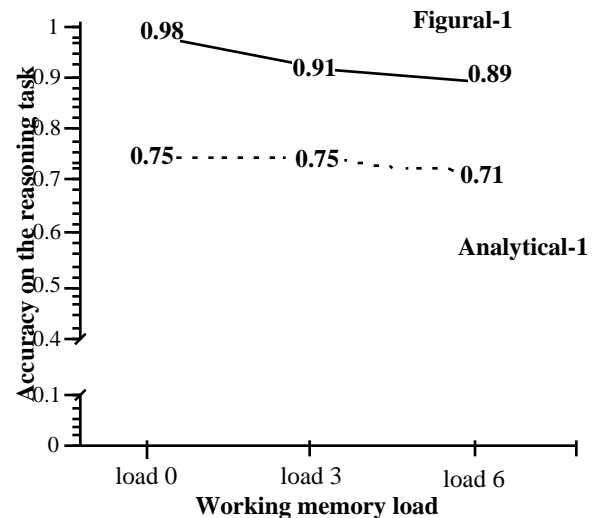

Figure 6. Mean accuracy on the reasoning task according to memory load and problem type for the two-dimensional problems.

One-dimensional problems. Mean accuracy as a function of memory load and problem type (figural-1 and analytical-1) is shown in Figure 6. Two planned orthogonal comparisons for both problem types were carried out. More specifically, the contrasts were (a) 3-load vs. no-load condition and (b) 6-load vs. lower load conditions.

For figural-1 type of problems, the comparison between the no-load and the 3-load conditions was found significant ($t = 1.804$, d.f. = 60, $p < 0.05$, one-tailed). The second comparison between the 6-load and the lower loads was not significant ($t = 1.620$, d.f. = 60, $p > 0.05$, one-tailed).

For the analytical-1 type of problems, none of the above comparisons was significant ($t = 0.069$, d.f. = 60, $p > 0.4$, one-tailed, for the first contrast and $t = 0.664$, d.f. = 60, $p > 0.2$, one-tailed, for the second contrast).

Table 2. **Different measures collected for solution latencies for the reasoning task and probe accuracy on the memory task according to problem type.**

Measures	Two-dimensional problems						One-dimensional problems					
	Figural-2			Analytical-2			Figural-1			Analytical-1		
	no-load	3-load	6-load	no-load	3-load	6-load	no-load	3-load	6-load	no-load	3-load	6-load
Solution latencies												
Median (in sec)	7.53	7.34	9.36	13.74	12.15	16.92	3.57	3.70	4.13	7.99	7.84	9.20
SD	5.74	8.19	8.21	18.01	18.05	15.40	1.72	1.49	3.04	9.06	8.35	12.758
Percent outliers	5.70%	3.40%	4.50%	4.50%	8.00%	4.50%	2.30%	4.50%	4.50%	5.70%	9.10%	6.80%
Memory probe accuracy	-	98.9%	92.0%	-	98.9%	96.6%	-	95.5%	93.2%	-	97.7%	94.3%

Discussion

The results suggest that the requirement that multiple operations be carried out simultaneously within a task is not sufficient by itself to necessitate executive control over attentional resources. An indication for this comes

from the profile of performance for the figural-2 problems: there was no decrement on the reasoning performance when a concurrent working memory load of three items was introduced. Since that specific type of problem has been shown to require executive resources (Prabhakaran *et al.*), if multiple operations require additional executive resources, decrements in performance should occur whenever the performance of a secondary task is required. This should be expected since the number of multiple operations that have to be carried out would be increased by the additional operation for maintaining the three working memory task items. However, the lack of such interference in the 3-item working memory load condition shows that the need for multiple operations are not indicative of executive component involvement in a task. Interference, suggesting the need for executive control, occurred only when the secondary task reached certain critical level of working memory load (six items).

In addition, the results also show that dual task performance by itself is also not a sufficient indicator for involvement of executive resources. Perhaps the strongest evidence for that was provided by the pattern of performance during the one-dimensional problems: even when during performance of such one-dimensional problems the concurrent memory load was increased from three to six items, the two tasks did not seem to interfere with each other, as shown by accuracy on the reasoning task performance. Since a working memory load of six items for this task has been shown to require brain areas related to executive functions, interference for this memory condition should have occurred if the two tasks by itself necessitated the involvement of executive resources. However, such interference was not observed.

In contrast to the other type of reasoning problems, the analytical-2 problems showed a linear increase in interference with increase in the working memory load imposed by the secondary task. However, it should be noted that in this case the interference in the 3-load condition was predicted on the basis of overlapping activation in Broca's area, and not in the dorsolateral prefrontal cortex, only the latter of which is thought to be involved in executive functions. In this way, that type of problem provided an example of how the interference between two tasks may appear to indicate the need for executive resources for the performance of two tasks simultaneously. The result for that type of problem suggests a possible explanation of why dual tasks have sometimes been found to be indicative of the need for executive processes and why sometimes they have been found not to indicate such a need (this point is discussed below).

General Discussion

As discussed in the introduction, numerous studies of the central executive system of working memory have generally found that its participation is required whenever the task being performed reaches certain level of complexity. There have been different attempts to define this complexity level in quantitative terms so that this level can be identified and the need for central executive resources predicted on the basis of task properties. Three task features were listed previously as appearing most frequently in defining complex tasks, and one of them - the multiple processing operations characteristic - was shown by results here to be, by itself, not sufficient for successful characterization of this complexity level. However, the other two characteristics - the multidimensional stimulus consideration and the maintenance of working memory information at or above certain critical level - were shown to successfully predict the level at which need for central executive resources occurs.

It is interesting to speculate what can be common between those two task properties. What mechanisms could be shared between the process of multidimensional stimulus evaluation and the maintenance of increased working memory load? If we go back to the original model of a Supervisory Attentional System, which was assumed to specify the functions and properties of the central executive, it can be seen that a major feature of the model, and a main mechanism according to which the Supervisory Attentional System is assumed to carry out its functions, is the mechanism of *switching* between different schemas, that is, of temporary inhibition of the currently active schema in order for another schema to be selected for executing.

In general, the switching between different schemas can be defined as the process which is needed whenever some information about the stimulus needs to be maintained, even though attention needs to be temporarily shifted to some other elements in the environment. Thus the switching, or alternating between different schemas, can be easily viewed as the reason why multidimensional stimuli, and more specifically the consideration of multidimensional stimulus change, has been found to necessitate executive resources. The different stimulus attributes are likely to activate different schemas for processing, and in order to consider several attributes of the same object or situation, there will be need to alternate between those different schemas.

However, how would switching between schemas account for the need for executive control of attentional resources during the maintenance of sufficiently increased working memory load? First, it should be noted that the specific load which has been shown to necessitate executive resources for its maintenance seems to correspond to a load *at*, or *above* the working memory span. Such conclusions can be drawn not only from the hereby described imaging studies, but also from other studies using behavioural tasks. Thus, Halford, Bain, and Maybery (1984) found that interference between a reasoning task of increased difficulty and concurrent memory load occurred only for memory load at or above span.

Indeed, a question that still needs to be clarified is whether the central executive is involved in the maintenance *per se* of the additional load above span (that is, whether it is involved in the active *rehearsal* of this additional load), or whether it somehow facilitates the maintenance through an indirect means, by modifying structures at a lower level of the working memory hierarchy that are specialized for maintenance (the 'slave' systems). If we assume that it only exerts some influence on those lower level structure, as Norman and Shallice have described its functions, it could be speculated that the maintenance of working memory load at or above span would implicitly involve some form of switching between schemas. The well known strategy of chunking within short-term memory load implicate that people tend to group the items that they need to maintain into chunks and to rehearse those chunks separately, possibly alternating (or switching) between them.

The process of alternating between different schemas could also explain the contradictory results about dual tasks and whether or not they require executive resources by themselves. For instance, D'Esposito *et al.* found that DLPFC activation was specific to dual task performance, whereas Klingberg (in press) did not find activation in this area during the performance of two simultaneous tasks.

Depending on the specific properties of the two tasks, it could be expected that sometimes the two tasks would require switching or alternating between different schemas for their execution, and would therefore necessitate executive resources, but at other times it would be possible to simultaneously carry out both tasks without need to alternate between attending to one and attending to the other. For instance Halford *et al.* (1984) have argued that competition between reasoning and memory occurs only when the memory task entails some form of active processing (such as encoding) that occurs simultaneously with reasoning. Simple storage of a concurrent memory load or rehearsal does not interfere. In accordance with the need for alternating-between-schemas explanation for executive resources involvement, it could be argued that during encoding, when a secondary task is present, attention needs to be switched back and forth between encoding of the new task, and completion of the already initiated process of encoding of the first task. On the other hand, during the maintenance phase of a task, an automatic schema for maintenance of information has already been activated, and attention can be directed to a newly presented task, without need to be redirected back to the first maintenance task, since the latter can be carried out automatically.

Yet another definition of task complexity that has been proposed involves consideration of the relational complexity of processing and the need to integrate multiple relations during the performance of a task. Thus Halford (1984), as well as Robin and Holyoak (1994) have proposed that relational processing requiring the integration and thus the simultaneous consideration of two relations is dependent on frontal lobe structures. It should be noted that the idea of relational complexity of a task is closely related to the previously described idea of multidimensional stimulus change. Thus, when two relations among elements of a stimulus configuration need to be integrated, the process of simultaneous consideration of both of them, and within it, the process of switching between the different relations, can be viewed as analogous to the process when two different stimulus dimensions have to be considered simultaneously.

Conclusions

In general, it seems that all attempts to predict when executive resources would be required for the performance of a specific task, have specified some definition involving an implicit or explicit process of the switching back and forth between the execution of different schemas. Indeed, this is in accordance with the properties of the initially proposed Supervisory Attentional System (Norman and Shallice, 1980). However, even within this model, the tasks that require control of attentional resources have been specified only in very general terms - such as *planning, error correction,* and *overcoming of habitual responses.* The main argument made here is that all those otherwise difficult to characterize tasks, share a common property in that they all require the shift of attention among the different automatic schemas being executed during behaviour. Therefore, the need for such attention shifting could be proposed as the primary task feature which necessitates participation of central executive resources.

References:

Atkinson, R.C. and Shiffrin, R.M. (1968). Human memory: A proposed system and its control processes. In K.W. Spence and J.T. Spence (Eds.), *The psychology of Learning and Motivation* (Vol. 2). New York: Academic Press.

Awh, E., Jonides, J., Smith, E., Schumacher, E., Koeppe, R., and Katz, S. (1996) Dissociation of storage and rehearsal in verbal working memory: Evidence from PET. *Psychological Science*, 7, 25:31.

Baddeley, A. (1990) *Human memory: theory and practice.* Boston: Allyn and Bacon.

Baddeley, A. D., (1992a). Working memory. *Science*, Vol. 255, 556-559.

Baddeley, A. D., (1992b). Is working memory working? The Fifteenth Bartlett Lecture. *Quarterly Journal of Experimental Psychology*, 44A:1-31.

Baddeley, A.D., and Hitch, G. Working memory. In G.H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory.* New York: Academic Press, 1974.

Baker, S.C., Rogers, R.D., Owen, A.M., Frith, C.D., Dolan, R.J., Frackowiak, R.S.J., and Robbins, T.W. (1996). Neural systems engaged by planning: a PET study of the Tower of London task. Neuropsychologia. Vol.34, No. 6, 515-524.

Carpenter, P.A., Just, M.A., and Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological Review, 97,* 404-431.

Cohen, J.D., Forman, S.D., Braver, T.S., Casey, B.J., Servan-Schreiber, D., and Noll, D.C. (1994). Activation of the prefrontal cortex in a nonspatial working memory task with functional MRI. *Human Brain Mapping, 1,* 293-304.

Cohen, J.D., Perlstein, W.M., Braver, T.S., Nystrom, L.E., Noll, D.C., Jonides, J., and Smith, E.E. (1997). Temporal dynamics of brain activation during a working memory task. *Nature.* 386: 604-608.

Corbetta, M., Miezin, F.M., Dobmeyer, S., Shulman, G.L., and Petersen, S.E. (1991). Selective and divided attention during visual discriminations of shape, color, and speed: functional anatomy by positron emission tomography. *The Journal of Neurosciences, 11*, 2383-2402.

D'Esposito, M., Detre, J., Alsop, D., Shin, R., Atlas, S, and Grossman, N., (1995). The neural basis of the central executive system of working memory. *Nature.* 378:279-281.

Duncan, J., Burgess, P., and Emslie, H. (1995). Fluid intelligence after frontal lobe lesions. *Neuropsychologia*, 33: 261-268.

Growder, R.G., (1982) The demise of short-term memory. *Acta Psychologica, 50*, 291-323.

Halford, G.S., Bain, J.D., and Maybery, M.T. (1984). Does a concurrent memory load interfere with reasoning? *Current Psychological Research and Reviews 2,* Vol. 3, 14-23.

Halford, G.S. (1984). Can young children integrate premises in transitivity and serial order tasks? *Cognitive Psychology 16,* 65-95.

Jonides, J. Smith, E., Koeppe, R., Awh, E., Minishima, S., and Mintum, M. (1993). Spatial working memory in humans as revealed by PET. *Nature,* Vol. 363, 623-625.

Klingberg, T. (in press). Concurrent performance of two working memory tasks - potential mechanisms of interference. *Cerebral Cortex.*

Kyllonen, P., and Christal, R. (1990). Reasoning ability is (little more than) working-memory capacity?! *Intelligence,* Vol. 14(4), 389-433.

Mackworth, J.F. (1959). Paced memorizing in a continuous task. *Journal of Experimental Psychology, 58,* 206-211.

Manoach, D., Schlaug, G., Siewert, B., Darby, D., Bly, B.M., Benfield, A., Edelman, R., and Warach, St. (1997). Prefrontal cortex fMRI signal changes are correlated with working memory load. *NeuroReport 8,* 545-549.

McFie, J. (1960). Psychological testing in clinical neurology. *Journal of Nervous and Mental Diseases, 131,* 383-393.

Milner, B. (1982) Some cognitive effects of frontal-lobe lesions in man. *Philosophical Transactions of the Royal Society of London, Series B., 298,* 211-226.

Morris, R.G., Ahmed, S., Syed, G.M., and Toone, B.K. (1993). Neural correlates of planning ability: frontal lobe activation during the tower of London test. *Neuropsychologia 31:* 1367-1378.

Nelson, H. (1976). A modified card sorting test sensitive to frontal lobe deficits. *Cortex, 12,* 313-324.

Norman, D. A., and Shallice, T. (1980). *Attention to action: Willed and automatic control of behaviour*. University of California San Diego CHIP Report 99.

Owen, A.M., Doyon, J., Petrides, M., and Evans, A.C. (1996). Planning and spatial working memory: a positron emission tomography study in humans. *European Journal of Neuroscience 8:* 353-364.

Paulesu, E., Frith, C., and Frackowiak, R. (1993) The neural correlated of the verbal component of working memory. *Nature.* 362:342-345.

Petrides, M., Alivisatos, B., Meyer, E., and Evans, A.C. (1993). Functional activation of the human frontal cortex during the performance of verbal working memory task. *Proceedings of the National Academy of Sciences, USA, 90,* 878-882.

Peterson, S.E., Fox, P.T., Posner, M.I., and Mintun, M. (1988). Positron emission tomographic studies of the cortical anatomy of single-word processing. *Nature,* 331, 585-589.

Prabhakaran, V., Smith, J.A.L., Desmond, J.E., Glover, G.H., and Gabrieli, J.D.E (1997). Neural substrates of fluid reasoning: an fMRI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive Psychology 33,* 43-63.

Raven, J.C., (1965). *Advanced progressive matrices: Sets I and II.* London: Lewis.

Robin, N., and Holyoak, K.J. (1994). Relational complexity and the functions of prefrontal cortex. In M.S. Gazzaniga (Ed.), *The Cognitive Neurosciences* (987-997). Cambridge, MA: MIT.

Rypma, B., Prabhakaran, V., Desmond, J., Glover, G., and Gabrieli, J., (in press) Load-Dependent Roles of Cortical Regions in Maintenance of Working Memory

Shallice, T., (1982). Specific impairments in planning. *Philosophical Transactions of the Royal Society London B.* 298:199-209.

Smith, E.E., Jonides, J., and Koeppe, R.A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6,* 11-20.

Sternberg, S., (1966). High-speed scanning in human memory, *Science*, 153:652-654.

Walsh, K.H. (1978). *Neuropsychology: A clinical approach.* Edinburgh: Chirchill Livingstone.

Waltz, J.A., Knowlton, B.J., Holyoak, K.J., Boone, K.B., Mishkin, F.S., de Menezes Santos, M., Thomas, C.R., and Miller, B.L. (in press). A system for relational reasoning in human prefrontal cortex. *Psychological science.*