Chapter 7

Fractionating the central executive

There is no doubt that the component we labelled the central executive is the most important subsystem of the three-component working memory model, and the one that presents the most difficult challenge. My first attempt to analyse the executive (Baddeley 1986), comprised a rather tentative single chapter. My current attempt impinges upon at least half of the present book. It would be nice to be able to claim that this is because we now understand how the central executive functions. Sadly, but not surprisingly, this is not the case. However, there have been considerable strides made in a range of areas pertinent to an understanding of the central executive. Covering even a fraction of this work, however, would represent a major task extending well beyond my own relatively modest contribution to the topic. Of particular relevance to the concept of a limited capacity central executive is Cowan's (2005) assumption of a limited-capacity focus of attention capable of holding about four chunks of information, a view which we both regard as entirely compatible with the multicomponent model of working memory. Although Cowan and I are fundamentally in broad agreement, we differ in emphasis. Perhaps for historical reasons, I have tended to emphasize short-term storage, and to be influenced by neuropsychological evidence, while Cowan stresses the role of the focus of attention, and developmental approaches. His excellent book (Cowan 2005) is recommended as providing a much fuller account of the role of attentional capacity in working memory than that provided here. The work of Shallice (Shallice 2002; Shallice and Burgess 1996) is also broadly compatible, although it attempts a much more detailed fractionation than my own, and relies more heavily on neuropsychological, neuroimaging and computational approaches. Finally, there is a large and growing neurobiological literature on executive control, well represented by Stuss and Knight's (2002) *Principles of frontal lobe function*.

The next three chapters, however, have the much more modest aim of describing my own attempts to put more flesh on the concept of a central executive. They are based on an approach (Baddeley 1996), which identified four candidates as important executive component processes, namely the capacity to focus attention, to divide attention, to switch attention and to provide a link between working memory and long-term memory. The first three of these will be covered in the present chapter and the fourth in Chapters 8 and 9. Before beginning this survey, I will summarize some of the background evidence for the basic assumption of a central executive.

I have previously pleaded guilty to creating an executive that is virtually a homunculus, a little man in the head who takes all the important but difficult decisions. My justification for this is the same as that proposed by Attneave (1960). Provided we attempt to describe the functions performed by our homunculus, we can then set out on a policy of divide and rule, attempting systematically to give a plausible account of how each of these processes might be performed. This strategy of making the homunculus increasingly redundant will, one hopes, end by allowing us to dispense with him altogether. We are certainly not in a position to do that at present. However, I think it is becoming increasingly clear just how this might potentially be achieved. The chapters that follow, therefore, could be seen as providing tentative steps towards a pension plan for the homunculus.

7.1 The central executive as rag-bag

For at least the first decade after the Baddeley and Hitch (1974) paper, we concentrated principally on the phonological and visuospatial subsystems, simply because they appeared to offer much more tractable challenges than did the executive. Although not a particularly bold strategy, I would claim that it worked reasonably well over the short term. However, as acknowledged in Baddeley (1986), repeated referrals of problems to the executive, without even speculation as to how they might be dealt with, was becoming an embarrassment. This led me to adopt of the Norman and Shallice (1986) supervisory attentional system (SAS) model as a potential framework for the executive. However, unless this framework is used constructively within the WM model, it can still be argued that any appeal to the central executive concept does little more than indicate that the phenomenon in question probably depends upon some form of relatively flexible attentionally limited control system. One problem with the absence of a clearly formulated model of the executive is the danger that others will invent such a structure, labelling it the central executive, and then going on to argue against its plausibility. The assumed monolithic status of the executive is a popular example, despite the claim that 'It seems unlikely that the central executive will prove to be a simple unitary system.' (Baddeley 1986, p. 253). Kimberg *et al.* declare that 'by definition the central executive is unitary' (Kimberg *et al.* 1997, p. 187), presumably on the grounds that executive is a singular noun. A similar line of reasoning would lead one to conclude that the term government being singular by definition implies a dictatorship.

A similar line to that of Kimberg was taken by Parkin (1998) and is refuted by Baddeley (1998). I assume that the central executive can in common with the other components of working memory, be fractionated into subcomponents. However, if the multicomponent model is to continue to develop, it is essential that the nature and function of the central executive be addressed.

7.2 Executive processes and the frontal lobes

In recent years, much of the research carried out on executive function has related it to its putative anatomical locus within the frontal lobes. Data from patients with frontal lobe damage played a crucial role in the development of the SAS model (Shallice 1988), and in its adoption as part of the working memory model (Baddeley 1986). The assumption that executive processes depend critically upon frontal lobe function has since received overwhelming support (for review, see Roberts *et al.* 1998; Kane and Engle 2002; Stuss and Knight 2002).

7.2.1 The dysexecutive syndrome

Single case studies of patients with bilateral frontal lobe damage provide some of the strongest evidence. Consider R.J., for example (Baddeley and Wilson 1988), who suffered substantial bilateral frontal damage after driving into the back of a horse van. After being unconscious for several days, he gradually recovered. R.J. was a civil engineer with an estimated premorbid IQ of 120. His language was well preserved, as was his visual and verbal memory span. He had good social skills and an excellent sense of humour. His LTM was impaired, and subject to extensive confabulation. He gave an elaborate and totally false recollection of his accident, and in a test of autobiographical memory, produced a number of bizarre 'recollections'. For example, he described writing to an aunt about the death of his brother Robin. When further questioned, he accepted that his brother Robin continued to visit him, but suggested that this was a later child who had also been called Robin. Although his confabulations changed from day to day, he gave every evidence of believing them strongly. For example, one weekend at home, he turned to his wife in bed and asked why she kept telling people they were married. When she protested that they were and had several children, he pointed out that that did not necessarily mean they were married. On being shown the wedding photographs, he conceded that the bridegroom did look like him, but denied that it actually was him. This was not a persistent delusion, but a single episode of confabulation, which he later denied.

One feature of frontal lobe patients is a tendency to perseverate. In giving an account of the accident in which he had sustained his head injury, R.J. included a lengthy conversation with a lorry driver with whom he had collided, in which each politely accepted responsibility.

R.J.: 'I am afraid it was my fault.'
Lorry driver: 'No, I was certainly to blame.'
R.J.: 'Yes but it really was me.'
Lorry driver: 'No. I insist that it was me to blame.'
R.J.: 'But I definitely made a mistake' etc.

After about ten of these, he eventually broke out of the loop and continued the narrative. Paradoxically, as well as tending to perseverate, such patients are readily distractible, showing evidence of what is sometimes termed utilization behaviour, whereby seeing an object is enough to encourage them to utilize it, regardless of how socially appropriate it might be, for example, picking up and using a comb that happens to be lying on the desk, or leaning over and drinking the examiner's cup of tea (see also Chapter 17).

The Norman and Shallice model captured this pattern of deficits by assuming that action is controlled at two levels. Much of our behaviour is dependent on overlearned existing schemata, which are largely under stimulus control. Novel behaviour or actions in emergency are dependent on a second process, the supervisory attentional system (SAS) which is normally capable of overruling any habitual action which appears to be leading to undesirable behaviour. The SAS is also capable of searching for possible solutions under circumstances where there is no available habitual response. We will return to this model and its subsequent extension later in the chapter. Before doing so, however, it is perhaps worth briefly describing some of the many alternative formulations that have been presented, usually based on speculation about the structure and function of the frontal lobes.

7.2.2 Neuroanatomical approaches

One influential account of executive control in working memory is presented by Goldman-Rakic (1988), and based on experiments using single cell recording to study working memory in awake monkeys (Fuster and Bauer 1974; Funahashi *et al.* 1989). She identified certain cells in the frontal lobes which are active only when the monkey is successfully remembering a cued location prior to a delayed response. She found other cells that code other types of sensory information, for example, shape versus location, proposing a model of working memory as a system for the online processing of information or behaviour in the service of a wide range of cognitive functions. She proposes that working memory is iteratively represented across a number of autonomous subdivisions, each with its own executive control system. This allows the system to integrate attentional, memorial, motor and very possibly affective dimensions of behaviour.

If extended to humans this model would appear to propose that the articulatory loop, for example, has its own central executive. This simply does not seem to fit either the neuropsychological data nor that based on normal function, both of which suggest a clear separation between phonological and executive processes, although of course the two do interact. I suspect the difference in emphasis between Goldman-Rakic's proposal and my own stems from the level of analysis, single cell recording versus complex behaviour analysed at a system level.

In general, both neuropsychological and neuroimaging evidence appears to support an organization based on function rather than modality (Tulving *et al.* 1994; Owen 1997; Smith and Jonides 1997). The separation of modality of presentation from the nature of the processing is particularly clearly illustrated in the case of language processing, where for example visually presented letters tend to be encoded phonologically (Conrad 1964) and where spoken sequences may be encoded visuospatially (Brooks 1967; Baddeley and Lieberman 1980). Goldman-Rakic's single unit recording studies were, of course, carried out on monkeys whose phonological loop, if it exists, is unlikely to play a major role in their memory performance.

There is no doubt however that Goldman-Rakic's work has had a major positive influence on the study of working memory, linking elegant neurophysiolgical studies on monkeys with concepts and techniques from human cognitive psychology and neurospsychology. Considerable progress is being made in understanding the functions of the frontal lobes based on animal studies, neuropsychological research and work using neuroimaging techniques (see Roberts, Robbins and Weiskrantz [1998] for some excellent examples of such progress).

7.2.3 Computational modelling of executive control

One approach is to continue to refine and develop earlier models by combining neuropsychological data and computational modelling. A good example of this is the continued development of the Norman and Shallice (1983) model which was computationally simulated by Cooper, Shallice and Farringdon (1995). They showed that adding 'noise' to the system simulates the effect of damage to the frontal lobes producing behaviour analogous to the neuropsychological syndromes of action disorganization and utilization behaviour found in patients with frontal lobe damage (L'Hermite, 1983). Shallice (2002) attempts to specify in greater detail the way in which the supervisory component might operate, providing a complex model involving three principal stages involving four temporally distinct phases and some eight different processes. At the core of the system is the generation and implementation of new temporary schemata that correspond phenomenologically to what we think of as strategies. As such they correspond to what Miller *et al.* (1960) refer to as 'plans'.

A broad outline of the Shallice (2002) model is shown in Figure 7.1 in which Stage 1 is responsible for the construction of temporary new schemata. Its subprocesses involve setting goals, generating schemata, which in turn may be influenced by retrieval from episodic memory, and by longer-term strategies. Stage 2 involves implementing new schemata that are held in what is termed a 'special purpose working memory'. This is followed by a third stage of assessment and verification of the new schema, which may result either in its verification and use, or in its rejection and a repetition of the schema generation phase.

The operation of the model may be illustrated by performance on the Brixton spatial anticipation test (Burgess and Shallice 1996c), a non-verbal analogue of the Wisconsin Card Sorting task which is sensitive to the effects of frontal lobe damage. It comprises a 5 × 2 array of circles, of which one is filled and the remainder unfilled. The subject has to decide which circle will be filled next, a process that is determined by one of eight different abstract rules, for example, the next circle beneath, or possibly an alternation between two circles. The task produces three scores, (a) number of correct responses, (b) number of bizarre responses of a type never given by control subjects, and (c) number of occasions on which the subject switches from a rule at a point when it is still operating successfully. Measures a and b correlate highly with each other ($r = 0.6$) whereas c correlates with neither a ($r = 0.13$) nor b ($r = 0.13$). All three measures, however, show impairment when patients with frontal lobe damage are compared with patients with matched WAIS intelligence performance, but whose lesions are more posterior. Shallice and Burgess suggest that both number correct and number of bizarre responses reflect failures of strategy generation, implicating impairment at Stage 1, while score c reflects a failure of Stage 2 to implement the schema.

7.3 Working memory and executive processes

As a cognitive psychologist, I feel I ought to be able to contribute to an understanding of executive processes in a way that is complementary to that of more neurobiological or computational approaches. In my own case, since I have not had good access to patients with clearly delimited frontal lobe lesions, or to convenient local neuroimaging facilities, I have concentrated principally on normal subjects, together with research on patients suffering from Alzheimer's disease (AD). One approach (Baddeley 1996) was to attempt to go back to first principles and identify processes that any executive system would require if it is to function effectively. Having identified such subprocesses, I then attempted to find a range of tasks on which they might reasonably be expected to depend. If the executive processes postulated were indeed fundamental, then

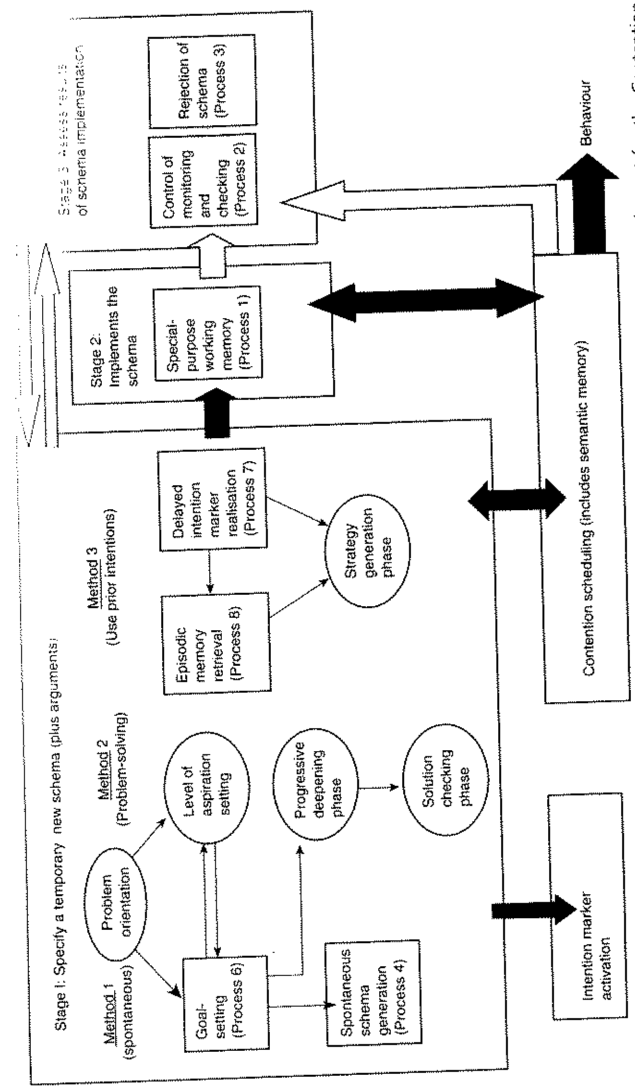

Fig. 7.1 The Mark II Supervisory System model developed by Shallice and Burgess (1996). All of the diagram (except for the Contention Scheduling component) concerns supervisory system processing. Within the large rectangle representing different stages of Supervisory System operation, temporally distinct phases of Supervisory System operation are represented by ellipses (reprinted from Shallice (2002), Fractionation of the Supervisory System in D. T. Stuss and R. T. Knight (eds) *Principles of frontal lobe function*, p. 263: New York, Oxford University Press). Reproduced with permission from Oxford University Press and the Royal Society.

they should operate across modalities and be applicable to a range of situations and tasks. I identified four candidate processes, namely the capacity to focus attention, the capacity to divide attention between two concurrent tasks, the capacity to switch attention from one task to another, and finally the capacity to integrate working memory and LTM (Baddeley 1996c). The first three are discussed below, and the fourth postponed until the next chapter. The study of attention is, of course, a field that has been extensively investigated (see Pashler [1998] for a recent overview). What follows is not intended as a review of this extensive and highly developed field, but simply as an account of my own attempt to form a much needed bridge between the study of attention and the analysis of the central executive.

7.4 Focusing the limited capacity

The capacity to direct and focus attention is perhaps the most crucial feature of working memory. The evidence that the system has a limited capacity is in general overwhelming, which is not to deny that under certain highly constrained conditions, two complex tasks may be performed simultaneously. A good example of this is the demonstration by Allport *et al.* (1972) of the capacity of an expert pianist to sight read and play a musical score and shadow prose at the same time with little or no apparent interference. Considered from the viewpoint of the Norman and Shallice model, one assumes that both of these tasks could, for this subject at least, be run using highly practised existing schemata, which can be interleaved with relatively little demand on the SAS system. There seems little doubt that a less accomplished pianist would show interference.

7.4.1 Attentional control of complex tasks

Of the many demonstrations of limited attentional control capacity, let us consider one, the study by Robbins *et al.* (1996) of the performance of moderate and highly skilled chess players. The work was prompted by a study by Holding (1989), who demonstrated that counting backwards in threes interfered with the retention of chess positions, and concluded that this reflected the importance of verbal coding. We challenged this interpretation, using dual task methodology to test other hypothesis. Both moderate and highly skilled players attempted to retain a briefly exposed position, either under control conditions, or while performing a series of concurrent secondary tasks designed to interfere with each of three components of working memory. Articulatory suppression was used to disrupt the phonological loop, a spatial tapping task was employed to disrupt the sketchpad, and randomly generating sequences of numbers were used to disrupt the central executive.

As expected, memory performance was highly correlated with chess skill. However, both expert and novice groups showed the same pattern of disruption from the secondary tasks, namely no impairment from articulatory suppression, a moderate disruption from spatial tapping, and a substantial drop when verbal random generation was required, suggesting that Holding's earlier result reflected the executive demand of backward counting, rather than disruption of verbal processing as he proposed.

A second experiment presented our novices and experts with a position from a middle game, requiring them to choose the best next move. Again, performance correlated with chess skill rating, and was again uninfluenced by articulatory suppression, but impaired by both spatial tapping and random generation. Indeed, the required rate of concurrent random generation had to be reduced in order to allow the subjects to perform at all adequately. Broadly equivalent results, namely little evidence of verbal coding, together with reliance on visuospatial and executive skills, are also reported as part of an extensive study of the cognitive psychology of chess by Saariluomo (1995).

The concept of a limited capacity attentional system is at least as old as cognitive psychology (Miller 1956; Welford 1956; Broadbent 1958; Fitts and Posner 1967; Neisser 1967). However, it is not simply the case that the more difficult the task, the greater its attentional demand (Allport *et al.* 1972; Logie *et al.* 2004). In a continuation of our chess studies, for example (Baddeley and Robbins, unpublished data), we gave our subjects the task of briefly viewing a middle game and deciding whether white or black had the advantage. This is quite a difficult task, which correlated with chess expertise. However, performance was not impaired by a demanding concurrent load. We assumed that this was because there was insufficient time to perform a systematic analysis of the position, hence forcing the subjects to rely on a relatively automatic pattern recognition-based positional judgement. Consistent with this was our observation that reducing the amount of available time for the judgement had no impact on performance.

7.4.2 Practice and automaticity

A second variable that interacts with ongoing executive demand is degree of practice. In a study of stimulus-independent thoughts, the tendency to let the mind wander, Teasdale *et al.* (1995) demonstrated that performing an unfamiliar task was sufficient to disrupt such thoughts, whereas performing the same task after a number of further practice trials had no such effect. Such a result is consistent with the classic demonstration of Schneider and Shiffrin (1977) that repeated experience of a limited set of stimulus-response mappings will reduce the attentional demand of the task in question. In a task using prisoners, who presumably had time on their hands to practice, Mowbray and Rhoades (1959) investigated the effect of prolonged practice on Hick's Law. This states that, given a task that involves reacting as quickly as possible, for example by pressing a key in response to an associated light, reaction time increases logarithmically with the number of stimulus-response alternatives. Hick proposed that the slope of the function indicates the rate at which the subject is able to process information. After sufficient practice however, the prisoners achieved zero slopes. Given sufficient practice, it seems that the demand for attentional control becomes minimal, as habit-based automatic processes become ever more efficient.

Yet another complicating factor is the strategy adopted. The capacity to generate examples from a semantic category such as animals appears to be an executively demanding task. It is highly sensitive to frontal lobe damage (Milner 1964) and is readily disrupted by a concurrent task such as choice reaction time (Baddeley *et al.* 1984b), or random generation (Baddeley *et al.* 1998b). Rosen and Engle (1997) found, as one might expect, that subjects with high working memory spans scored well on this task, and showed clear impairment when required to perform a concurrent task. Paradoxically, however, low span subjects showed no secondary task disruption, presumably because unlike high span subjects, they were not using an attentionally demanding strategy, even under control conditions. The question of strategy is one that pervades the working memory literature, since the essence of the working memory system is its flexibility. However, the strategy explanation can be criticized as potentially allowing a post hoc explanation of virtually any unwanted experimental findings. Such explanations are much more convincing when they are supported by subsequent studies that explicitly control strategy (e.g. Hanley and Bakopoulou 2003).

7.4.3 Random generation

One of the unexpected benefits from adopting the Norman and Shallice SAS model was its capacity to give an account of earlier data on the capacity for generating random sequences. This proves to be a very demanding task. When asked to produce a random sequence of letters, for example, subjects tend to favour some letters over others, to produce too many sequences in alphabetic order such as *AB*, *RS* and *XYZ*, and to avoid immediate repetitions such as *AA* and *RR* (Towse 1998; Tune 1964). Such deviations from randomness increase both with rate of generation, and in dual task conditions, with the demands of the secondary task (Baddeley 1966c). Random generation resisted earlier attempts at interpretation within a more conventional stimulus-response framework, but appeared to lend itself to interpretation with the Norman and Shallice model, based on the distinction between responding on the basis of ingrained habits, and the capacity of the SAS to intervene. Hence, given the instruction to produce a stream of letters, the natural tendency would be to use the alphabet recitation schema, or to produce common acronyms such as *USA* and *CIA*. Given the instruction to make the sequence random, however, there would clearly be a need to avoid such stereotyped sequences, producing a tension between what is easy to retrieve, and what is optimal. Exploring the nature of random generation, therefore, seemed to offer the possibility of throwing light on the fundamental processes involved in the executive control of action.

In a subsequent series of experiments, we chose to tackle the problem by moving away from the verbal generation of alpha-numeric information to the requirement to press an array of ten keys at random (Baddeley, *et al.* 1998b). There were two reasons for this. The first was practical, since it meant that subjects entered their responses directly into the computer, thereby simplifying analysis. The second was more theoretically oriented, and related to our assumption that executive processes were relatively modality-free. If so, we should observe broadly similar phenomena regardless of whether the subject was uttering a sequence of numbers or letters, or pressing a sequence of keys.

Our first experiment, therefore, studied the influence of rate of randomization on the redundancy of the resulting response sequence, using either the digits 0-9, or ten keys, arrayed to match the shape of the two hands. Although verbal generation was somewhat more random, the effect of generation rate was equivalent, with faster generation leading to statistically less random sequences. As in the earlier study (Baddeley 1966c), we also found that as speed increased, the number of stereotyped responses became greater. In the case of key pressing, the preferred sequences comprised first of all the homologous key on the other hand, followed by adjacent keys on the same hand, and then adjacent on the opposite hand. We combined our randomized key-pressing task with concurrent verbal tasks, to see if degree of randomness was sensitive to concurrent task demand. This indeed proved to be the case. The requirement to generate items from semantic categories is known to be both attentionally demanding (Baddeley *et al.* 1984) and sensitive to frontal lobe damage (Milner 1982). As a concurrent task, it substantially reduced the randomness of key pressing. Even more disruptive was the requirement to perform a concurrent intelligence test (Baddeley *et al.* 1998).

At this point we were thinking rather generally in terms of some specific executive component which was required both for generation and for other important cognitive tasks. In an attempt to test this rather vague hypothesis, we decided to combine random keyboard generation with the requirement to verbally produce random digit sequences. We expected this to lead to the dramatic overload of the assumed specific component, and the breakdown of performance. We were in for a surprise. When combined, keyboard randomization was impaired, to about the same extent as would occur if it were combined with verbal category generation, but random number generation was only minimally disturbed.

In order to account for this unexpected result, we were forced to think in more detail about the processes involved. We suggested that random generation involved at least four processes, selecting a 'retrieval plan', operating it, checking the output to avoid stereotypes or repetitions, and if necessary switching to another retrieval plan. There is evidence to suggest that once a retrieval plan is specified, the retrieval process itself is relatively undemanding (Baddeley *et al.* 1984; Craik *et al.* 1996; Naveh-Benjamin *et al.* 2000). Furthermore, if we assume that verbal and motor retrieval plans do not mutually interfere to any great extent, then it seemed likely that the imposed load must have had effect on either the switching or the checking stage, or perhaps both. Both these stages occur after a response has been emitted. Impairment of either of these processes would therefore not produce a dramatic immediate disruption, but would simply increase the redundancy of the output by not switching sufficiently frequently. Comments by subjects suggested that stereotyped sequences and deviations from randomness in verbal generation are much more noticeable than in key pressing. Indeed, some subjects claimed (wrongly) that the requirement to perform a demanding concurrent task made keyboard generation *easier*, something that was not ever claimed with verbal generation. It seems likely therefore that our subjects were monitoring and maintaining verbal generation at the expense of deterioration of the less salient manual task.

We decided to test our switching hypothesis by combining keyboard generation with a task that itself involved frequent switching, arguing that this would disrupt the switching component, and hence dramatically impair performance, even though the switch itself was highly predictable. We opted for a task that was based on a commonly used neuropsychological task, the Trails Test, which is assumed to measure task switching. It involves an array of numbers or letters scattered across a sheet of paper. In the basic condition, Trails A, the subject is presented with either numbers or letters, and instructed to start with the first item, for example, number 1, join it to number 2 by pencil, continuing to trace the path and connecting the numbers in ascending order. In the case of letters, the subject begins with A and moves through the alphabet. In Trails B, the switching condition, the subject is shown a mixed array of numbers and letters, and required to alternate, beginning with A, joining it to 1, which then

is joined to B, then to 2, etc. As we were studying manual generation, we devised a verbal equivalent of the Trails Test. In the Trails analogue, the subject either recited the letters of the alphabet, or counted. In the crucial Trails switching condition they were asked to produce alternating spoken sequences such as A, 1, B, 2, C, 3, etc. When we combined this verbal alternation task with manual random generation, we found a very substantial decrease in randomness, a result that we regarded as consistent with our assumption that the switching component of the trails task was disrupting the switching stage of random generation. This in turn led us to the hypothesis that the capacity to switch attention might represent a basic and separable executive function. We set out to test this hypothesis: again using dual task methodology.

7.5 Task switching and the central executive

In 1927, Jersild published an extensive series of experiments that attempted to measure the attentional cost of switching from one task to another. A typical experiment involved a list of pairs of digits, with subjects asked either to add the two digits in one condition, to subtract the second digit from the first, or to alternate addition and subtraction from one digit pair to the next. He found that switching led to substantial slowing of performance. Somewhat surprisingly, his work was neglected for almost half a century, until Spector and Biederman (1976) reintroduced the arithmetic task switching paradigm, demonstrating among other things that the cost of switching was substantially reduced, if not removed, by providing the appropriate plus and minus cues on the response sheet, rather than simply instructing the subject to alternate.

7.5.1 Switching and the central executive

Almost 20 years then went by before the issue was raised again in an influential paper by Allport *et al.* (1994), which directly challenged the widely held view that task switching was an attentionally demanding process, dependent on a limited capacity executive control system. This view was in turn challenged by Rodgers and Monsell (1995) who found that their subjects could reduce the cost of switching given an appropriate cue and sufficient time to process this information. This has subsequently become an extremely active research area, in which the proposal that switching might reflect the operation of the unitary executive function has proved over-optimistic (see Monsell [2005] for a recent review). For present purposes, however, rather than review this complex and developing literature, I will focus on a series of our own experiments that, although unsuccessful in throwing great light on the mechanisms underpinning task switching, caused a valuable modification in my own conception of working memory.

Our attempt to investigate the possibility of a specific switching component within the central executive used the very basic Jersild paradigm in which alternation is required within a printed list of items. We wanted a task that could be used clinically, involving minimal equipment and a task that could easily be understood and readily be performed by both normal subjects and patients suffering from dementia. We opted for a simple paper and pencil task that we found to give robust results, even though it did not allow the detailed measurement of individual responses that would have been possible with more sophisticated techniques. The task involved simply presenting the subject with a column of single digits. In one condition, the requirement was to add 1 to each digit, a second condition involved subtracting 1 from each, while the crucial switching condition required alternation between addition and subtraction. We found clear evidence of switch cost, even when the appropriate plus and minus signs were provided with each sum. We found that the cost of switching was particularly high for AD patients. We decided to explore the task in more detail using normal subjects, studying switching while performing a range of secondary tasks (Baddeley *et al.* 2001b).

Our first experiment studied the effect of omitting or including the plus and minus signs, combining this with simultaneous performance of the verbal trails task described previously. We reasoned that if there is indeed an executive component specialized for switching, then it should be dramatically overloaded by the need to switch on both arithmetic and verbal trails tasks at the same time.

We chose not to use our previous 1-A-2-B-3-C task, since we were concerned that the counting component might well interfere directly with the addition or subtraction involved in the main task. Instead, we required the recitation of items from two other familiar sets, namely days of the week and months of the year. Hence, subjects would either recite the days or the months, or would alternate (e.g. *January-Monday-February-Tuesday-March-Wednesday*, etc.). We did, however, need one further control. It seemed possible, though unlikely, that simply suppressing articulation might impair performance. We therefore included an articulatory suppression condition in which subjects repeatedly recited in canonical order either the days of the week or the months of the year.

Our results fell into two categories. When plus and minus signs were provided, offering a direct cue as to whether that specific item required addition or subtraction, there was a modest but highly reliable effect of switching, which was slightly increased by the addition of the verbal trails task, but not by articulatory suppression. Switching did, therefore, seem to place something of a load on executive processes, but the effects were far from dramatic, and hence not supportive of the idea of a specific switching subprocess that might have been greatly disrupted by the requirement to perform two concurrent switching tasks.

When signs were absent, however, much more dramatic impairment was found. Somewhat surprisingly, there was substantial disruption even from the articulatory suppression condition, suggesting an important role for the phonological loop in controlling action. It was however, suggested by a referee of our submitted paper, that reciting months of the year, or even days of the week, might not be so easy a task as we had assumed. This proved to be the case, since the effects observed were indeed reduced when articulatory suppression involved simply repeating the word 'the', although the overall pattern remained (Baddeley *et al.* 2001b).

7.5.2 An executive role for the phonological loop?

In a subsequent study Emerson and Miyake (2003) have extended this result, varying the difficulty of the addition and subtraction task, and comparing switching between two and three operations. They replicated the substantial effect of articulatory suppression. Increasing either difficulty level or number of switching operations increased overall processing time, but these factors did not interact with the effect of articulatory suppression. A further experiment varied the degree of cueing of the switched arithmetic operation. Each item was either presented without a cue, with a clear plus or minus cue, or in an intermediate condition presented in a colour which indicated either addition or subtraction. Switch cost depended on the strength of the cue, being greatest in the no-cue condition, and least with the arithmetic signs, but again the effect did not interact with the presence or absence of articulatory suppression.

Emerson and Miyake interpret their results in terms of the use of speech cues to control behaviour: 'Because (inner or private) speech allows generation of serial performances that have reliable properties such as duration, repeatability, and evocation of related information, private speech is well suited to serve a variety of control functions' (Carlson 1997, p. 168). Its advantages include the fact that it is inherently sequential, and hence good for keeping track of ordered actions. The phonological loop holds a limited number of items which it keeps readily available to conscious awareness. The verbal content of the phonological loop readily triggers other responses, including both semantic associations and task relevant intentions. Subvocal articulation is highly practised and resistant to interference. Finally, it has the advantage of being maintained with relatively little attentional demand.

Further evidence for the use of verbal control in task switching comes from clinical studies using the Wisconsin Card Sorting Task in which patients have to sort cards into categories, working out the correct categorization from feedback presented by the tester. Once a category has been achieved, the tester switches, leaving the patient to detect the switch and identify the next category (Milner 1964). Patients with frontal lobe damage tend to have difficulty in switching from one category to the next, suggesting a dependence on executive processes. Dunbar and Sussman (1995) found that switching was also impaired by articulatory suppression while Perry *et al.* (2001) noted that instructing schizophrenic patients to verbalize their hypotheses improved their performance. Finally, there is evidence that switch costs may be increased in aphasic patients, with degree of disruption correlating with extent of speech impairment (Mecklinger *et al.* 1999).

The proposal that speech may play an important role in the control of action is not of course a new one. It formed an important component of Vygotsky's (1962) approach to cognitive development, emphasizing the role of speech in the development of thought processes. Luria (1959) further developed these ideas, carrying out an ingenious series of experiments on the role of speech in the control of action. He employed a task in which a child is instructed to squeeze a bulb when a red light flashes, but not to squeeze to a blue light. Below the age of three, children tend to press in response to both lights even though they are able to report the instruction correctly, and to perform the task if the tester gives the instruction 'press' when the red light comes on, and 'don't' to the blue light. By three-and-a-half, children begin to be able to make the appropriate verbal responses, but still do not perform the action. Between four and five, children finally learn to accompany their speech with the appropriate action, and in due course to perform the action without speech. Luria (1959) went on to show similar phenomena in neuropsychological patients with frontal lobe damage, resulting in the subsequent development of an approach to neurological rehabilitation in which the patient is encouraged to control action by overt self instruction.

Returning to the role of attention in task switching, there is some indication that concurrent executive demand from such tasks as verbal trails or random generation can interact with switching, suggesting that under certain circumstances at least, switching may be attentionally demanding. However, there is no strong evidence for a specific component of the executive that is exclusively devoted to switching. Indeed, switching under certain circumstances actually appears to enhance performance. Subjects required to write sequences of letters as rapidly as possible respond more slowly when the same letter is repeated (*A, A, A, A*, etc.) than when alternating (*A, B, A, B*, etc.), which in turn is slightly slower than longer repeated sequences (such as *A, B, C, D, A, B, C, D*, etc.), a result that appears to reflect the build up of some kind of inhibition (Nohara 1965; Wing *et al.* 1979). Hence, although there are growing numbers of hypotheses as to the factors underlying task switching, I myself am inclined to agree with Rubenstein *et al.* (2001), who suggest that switching is not a general function, but a process whose costs or benefits are likely to vary depending on the precise situation and the strategy adopted by the subject to deal with it.

7.6 Division of attention as an executive skill

It is clearly the case that we need, on occasion, to split our attention across more than one task. For example, I am currently walking in the rain along a narrow road, dictating while holding an umbrella which I attempt to avoid skagging in the brambles, meanwhile listening for approaching cars which might just possibly not notice me. The latter activity is relatively undemanding, but given the possible consequences, potentially important. A similar potential multitask conflict occurs in driving while telephoning, an activity that has been shown to be dangerous, not principally because of the potential need to use one hand to hold the telephone, but because of the potential division of attention. As long ago as 1969, Brown *et al.* for example, showed that the need to perform a demanding verbal reasoning test had little or no effect on manual skill in steering between two markers, but had a substantial impact on the driver's capacity to judge whether the gap was wide enough. Difficulty in performing two tasks at the same time is consistent with the assumption of a specific cognitive capacity for sharing attention, but by no means forces this interpretation (see Bourke *et al.* [1996] for a discussion).

7.6.1 Dual task performance in Alzheimer's Disease

My own involvement with studying the capacity for dividing attention stemmed from collaborative research on the cognitive deficits associated with Alzheimer's disease. An initial study indicated that in addition to the well-established marked impairment in episodic LTM, our patients also showed deficits in both visual and verbal immediate memory (Spinnler *et al.* 1988). We speculated as to the possibility that this might reflect an underlying deficit in the central executive component that contributed to both our STM deficit in the central executive component that contributed to both our STM tasks, a conclusion that was consistent with a more detailed analysis of verbal STM in such patients by Morris (1984; 1986). The question arose, however, as to how to measure the proposed executive deficit.

Using the basic tripartite model of working memory, it seemed plausible to assume that the executive would be required if it were necessary to coordinate two or more separate activities. Furthermore, if one activity relied principally on the phonological loop, and the other on the sketchpad, then we should be able to avoid more peripheral sources of perceptual or motor disruption. Our first study used visuospatial tracking, in which subjects had to keep a stylus in contact with a moving spot of light. By varying rate of target movement, we could equate the level of performance of our three groups, namely patients suffering from the early stages of Alzheimer's disease (AD), elderly normal subjects matched for age, and young subjects. In each case, we set tracking performance at about 70per cent time on target. We combined tracking with each of three secondary tasks, one involving articulatory suppression, a second requiring the subject to press a foot pedal in response to an auditory stimulus, while a third required subjects to hear and repeat back sequences of random digits. In the case of the memory span task, by pre-testing, we were able to ensure that digit sequence length was set at span level for all three groups. Each of the three tasks was then combined with tracking.

We found no significant impairment in any group as a result of simple articulatory suppression. The two control groups showed a modest degree of decrement from concurrent reaction time and digit span tasks that was broadly equivalent for normal young and elderly subjects. The AD patients, however, showed a substantially greater disruption from the need to combine tasks (Baddeley *et al.* 1986). A subsequent study (Baddeley *et al.* 1991) involved a longitudinal study of patients. We found that as the disease progressed, their capacity to perform the tasks alone showed little change, whereas dual task performance declined systematically. Could it be the case that the dual task condition was just more difficult, and hence more sensitive to the effects of AD? This seemed unlikely, since increasing the level of difficulty of a unitary semantic judgement task did not make it more sensitive to the disease (Baddeley *et al.* 1991).

We interpreted our results in terms of a specific component of the central executive concerned with dual task coordination, which we argued was disrupted in AD. Unlike other cognitive capacities such as episodic memory, however, the capacity to divide attention appears to be comparatively preserved in normal ageing (see also Salthouse *et al.* 1998). If we could establish this firmly, then we would have achieved two things, theoretical progress in fractionating the central executive, together with a potentially useful clinical test that might be useful in deciding whether a forgetful patient was or was not likely to be suffering from AD.

In a review of the attentional deficits associated with AD, Perry and Hodges (1999) identified the capacity to divide attention as one of the strongest candidates for a separable deficit. As they pointed out, however, alternative interpretations could be offered, for example, in terms of level of difficulty or as just one example of a more general speed of processing deficit. Decline in speed of processing has been proposed as the principal deficit in normal ageing (Salthouse 1992; 1996), while a similar argument has been presented in the case of AD (Nebes and Brady 1985).

Two subsequent studies have addressed this issue. Baddeley *et al.* (2001a) again demonstrated that increasing level of difficulty did not necessarily make a task increasingly sensitive to AD. We compared simple and choice reaction time (RT), finding that young subjects, normal elderly and early AD patients all respond more rapidly when a single stimulus, a triangle, requires a single key press response (Simple RT) than when required to make separate responses to triangles and circles (Choice RT). Choice RT was also more sensitive to the effect of age, with elderly subjects more disrupted by increasing set size than young. There was, however, no evidence for this increase in RT to be disproportionately greater in patients than in elderly controls. In contrast, as predicted, we did find a disproportionate deficit in each of two dual task paradigms. One involved a manual box-crossing task analogous to tracking, in which subjects marked a chain of boxes on a response sheet, working as rapidly as possible while remembering and repeating back span length digit sequences.

The other task moved away from memory altogether. Subjects were given a visual search task comprising lines of pictograms. Each line was preceded by a target pictogram, and the subject was required to cross out any matching items on that line, before moving on to the next target and line. The concurrent task was analogous to that of a traveller sitting on a railway station and listening for the announcement of his destination. We chose the name *Bristol*, the city in which the study was run, embedding this among other familiar town names, and requiring the subject to call out 'Bristol' whenever the name was detected. The visual search and 'Bristol' tasks were performed singly and in combination. Both of our dual task procedures showed the standard effect, namely no significant decrement as a result of age, but a very clear dual task impairment in AD patients. This result emphasized both the replicability of our earlier finding, together with its generalization to tasks without any direct memory requirement.

A study by Logie *et al.* (2004) tackled the level of difficulty hypothesis more directly. Using the concurrent tracking and digit span paradigm, we titrated both tracking speed and digit sequence length to a point at which our young, elderly and patient groups were matched on performance when these tasks were performed individually. For each task, we then systematically varied the level of difficulty. In the case of tracking, we substantially reduced target speed to make it easier, or made it more difficult by increasing speed. We similarly varied the difficulty of the digit span task, either presenting fewer digits than span, or more than span. When the tasks were performed singly, all three subject groups behaved in the same way, with performance improving when the task was made easier, and deteriorating when it was made harder. The three functions, having been matched at span level or baseline tracking level, showed totally superimposed performance across our three subject groups, providing no support for the suggestion that simply increasing difficulty will make a task more sensitive to AD. In another study using the same subjects, the task was set at the easiest level for both tasks, and both single and dual task performance observed. Even under the easiest conditions, AD patients showed a significant dual task decrement, whereas control subjects showed no sign of impairment.

7.6.2 Is task-combination an executive skill?

We would claim, therefore, that our results show a prima facie case for regarding the capacity to combine tasks as being a potentially dissociable executive skill, one that is surprisingly well-preserved in the normal elderly, provided one matches young and old on individual task performance, but which is consistently impaired in AD patients. We do not wish to claim that it will not prove possible to detect an age effect; many studies have indeed claimed such an effect (see Riby *et al.* 2004 for a review). However, studies often fail to equate performance across groups on the individual tasks. It is therefore unsurprising that requiring the elderly to combine two tasks on which their performance is inferior causes even greater decrement than is found on either of the single tasks alone. Even when individual tasks are equated, an age effect may be detectable. Our results across a series of studies suggest, however, that any such effects appear to be, at most, slight, compared to the robust dual task deficit found in AD patients. We therefore suggest that the capacity to divide attention is a candidate component of the central executive, while accepting that only time will tell how widely our results can be generalized.

Fortunately, there already exists evidence of some generality, and of potential practical significance. Hartman *et al.* (1992), for example, applied our findings to the task of a physiotherapist treating an individual patient recovering from head injury. They compared the patient's capacity to perform a motor task alone with performance when accompanied by general verbal encouragement, or when accompanied by friendly conversation. Normal subjects were able to perform the task regardless of distraction. Head injured patients also showed no effect of general encouragement, but performance deteriorated when accompanied by conversation, an effect that was particularly marked in patients with frontal lobe damage. In another study, Alberoni *et al.* (1992) studied the capacity of AD patients to remember the content of videoed conversations, as a function of number of participants. We found a substantial effect of increasing number of speakers on the capacity of AD patients, but not controls, to follow a conversation. This finding is not of great theoretical significance, since overall conversational difficulty would be likely to increase with group size.

However, this result was selected by a publication for AD carers as being of clear practical relevance to relatives arranging visits to AD patients.

7.6.3 Does social behaviour involve multitasking?

Dual task performance measures were included in a study by Alderman (1969), who was concerned to understand why certain patients derived no benefit from a rehabilitation scheme for head injured patients with severe behavioural problems. He found that patients who did not benefit showed slightly poorer performance on a range of frontal lobe tests, but performed consistently badly on a series of dual task measures.

Further evidence for an association between behavioural disturbance and impaired dual task performance came from a study of patients with frontal lobe lesions (Baddeley *et al.* 1997). Patients were tested on the previously described task involving box-crossing and digit span. They were also tested on two measures that are commonly associated with frontal lobe damage, namely verbal fluency in which the subject must generate items from semantic categories, and the Wisconsin Card Sorting Test (WCST), in which patients must learn to sort on the basis of each of six specified stimulus dimensions, and then switch when that dimension is no longer treated as correct. In addition, patients were assessed independently for signs of dysexecutive behaviour, using both an interview and assessment of the patient's medical records to judge whether they showed the attentional deficits and disinhibited behaviour that is often associated with frontal lobe damage. The patients showed clear evidence of impairment on all three cognitive tests, and about half showed evidence of dysexecutive symptoms in their behaviour. These behavioural symptoms were significantly associated with poor dual task performance, but not with degree of deficit in either capacity to perform the WCST, or the verbal fluency tests, for which impairment was equally likely in dysexecutive and non-dysexecutive patients. It appears to be the case therefore that although impaired verbal fluency and WCST performance were, as expected, associated with frontal lobe damage, a separate frontally based capacity was reflected in both dysexecutive behaviour and impaired dual task performance. Why should this be?

One possibility is that adequate social behaviour requires a capacity for dual task performance, balancing one's own needs and desires with those of the people you are interacting with. It is equally possible, however, that the area of the frontal lobes involved in dual task performance and those required for adequate social interaction just happen to be anatomically adjacent. Whichever proves to be the case, this clearly appears to be an interesting area to investigate further, from both a theoretical and practical viewpoint.

7.7 Conclusions

To summarize, we began by proposing a general attentionally limited control system, the central executive, basing a good deal of our case on neuropsychological evidence, principally from patients with frontal lobe damage. This was followed by the consideration of three candidates for component executive processes. The first, a capacity to focus a limited capacity system, is quite broadly accepted as a feature of most current attentional theories (Pashler 1998). The second, a capacity to switch attention, on closer examination seemed unlikely to be based on a single executive subprocess. The third, the capacity to divide attention, appears more promising, though by no means firmly established. The fourth function proposed for the executive (Baddeley 1996), namely the capacity to link long-term and working memory, will be discussed in the next chapter.

Chapter 8

Long-term memory and the episodic buffer

Of the four functions that I suggested might be desirable in a central executive, three were characteristics of attentional control, namely the capacity to focus, to divide and to switch attention, while the fourth capacity was qualitatively different, namely that of interfacing working memory with long-term memory (Baddeley, 1996). Implicit in the first three is the idea of the central executive as an *attentional control system*, something that was made explicit by Baddeley and Logie (1999). Such a view differs from the initial concept, which regarded the central executive as comprising a limited capacity pool of *general* processing capacity that could be used for a range of functions including both attentional control and temporary storage. The modification to our original view stemmed from the fear that a general processing concept was simply too powerful, with too few constraints to generate tractable and useful questions. By treating the executive as a purely attentional system, it became easier to frame potentially fruitful questions, although as we have just seen, not necessarily to answer them at this stage with any degree of completeness. However, having banished storage from the executive, it became increasingly clear that we were left with a number of problems in tackling the fourth question raised, namely that of how working memory and long-term memory interact.

8.1 Some reductionist views

Before beginning the search for a link between working memory and long-term memory, we should consider a number of alternative views that would largely dispense with the question. One of these is the suggestion that WM is simply part of the system for processing language. This view tends to be taken by investigators whose primary interest is in language, and who regard temporary storage simply as a secondary feature of the systems involved. This is therefore partly a question of focus rather than content. However, it may lead to a neglect of those features of WM that are not language-based, as in the case of Allport's (1984) proposal that STM deficits in patients are caused by a subtle deficit in speech perception.