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Order and Disorder in Everyday Action:
The Roles of Contention Scheduling and Supervisory Attention

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Abstract: This paper describes the contention scheduling/supervisory attentional system approach to action selection and uses this account to structure a survey of current theories of the control of action. The focus is on how such theories account for the types of errors produced by some patients with frontal and/or left temporo-parietal damage when attempting everyday tasks. Four issues, concerning both the theories and their accounts of everyday action breakdown, emerge: first, whether multiple control systems, each capable of controlling action in different situations, exist; second, whether different forms of damage at the neural level result in conceptually distinct disorders; third, whether semantic/conceptual knowledge of objects and actions can be dissociated from control mechanisms, and if so what computational principles govern sequential control; and fourth, whether disorders of everyday action should be attributed to loss of semantic/conceptual knowledge, a malfunction of control, or some combination of the two.

Introduction

The cognitive requirements of the control of action appear to vary substantially between tasks. At one extreme, action control may appear to require little cognitive effort, as when driving a familiar car along a familiar route. At the other extreme, action control may demand constant attention to the task, as when a novice programmer is debugging a computer program or when a novice cook is attempting to prepare a roast meal for the first time. Norman & Shallice (1980, 1986) employed the phenomenological difference between these extremes to argue for the existence of two distinct systems for the control of thought and action. They argued that in routine situations behaviour is controlled by a relatively automatic system, which they referred to as contention scheduling (CS), but that a second system, referred to as the supervisory attentional system (SAS), could be invoked in situations requiring attention to detail (e.g., situations involving trouble-shooting, novelty, planning, decision making or the suppression of an habitual response). Shallice (1988) added a further source of evidence for a dual-systems approach: Engineering experience derived from Artificial Intelligence work on planning and problem solving suggests that a single control system for preparing and performing a plan is insufficient. More adequate systems employ separate sub-systems, operating in different ways, for the routine execution of plans and for the development of new plans. With the addition of one assumption — that there is a repository of basic or standard plans — the distinction between planning and performing a plan maps directly onto that between SAS and CS.

In fact, the control of action, even in the service of everyday tasks that are highly routinised, demands considerable computational sophistication (cf. Cooper & Shallice, 2000). This complexity stems in part from the requirement to co-ordinate or integrate perceptual information (for the location and identity of objects on which to act) and effector state information (for the selection of effectors with which to act) with goals, intentions, and plans, and to maintain goal-directed behaviour throughout a task.

To illustrate, consider the relatively simple "everyday" task of applying jam to toast. This may involve grasping a butter knife (with an appropriate grip), dipping it in the jam (and ensuring that a reasonable quantity of jam is captured on knife's blade), and applying the jam to the toast with several spreading actions. If the jam jar is closed prior to attempting the task, it is necessary to open it. This is best done prior to picking up the knife, as it is likely to require both hands. Furthermore, if several implements are available (as is often the case), most should be ignored in favour of a butter knife. If no butter knife is available, it may be necessary to suspend the routine while fetching an appropriate knife from a kitchen draw. Thus, even this simple task requires the detection and selection of appropriate objects, the suspension and subsequent resumption of activities (while fetching a suitable knife), the maintenance of goal/sub-goal relations while completing the task, the monitoring of task goals (to ensure that an appropriate amount of jam is applied, and to terminate spreading when the toast is covered with a sufficiently even coat of jam) and even simple planning (in determining that the jam jar should be opened before grasping the knife, or, if dealing with multiple slices of toast and limited jam, ensuring that each slice gets a share of the jam).

Given the complexity of the control of everyday activities, it is not surprising that the system or systems responsible are prone to error. Both Reason (1979, 1984, 1990) and Norman (1981) have catalogued slips and lapses in the everyday action of neurologically intact individuals and developed classification systems for the errors observed. Common error types include capture errors (when action is "captured" by a familiar but unintended routine), substitution errors (when one object or location is used in place of that which should be used), omission errors (where some crucial action or step is left out), perseverative errors (where an apparently correct action is unnecessarily repeated) and sequence errors (where correct actions are performed in an incorrect order, through, for example, anticipatory performance of a task-appropriate action).

It is also not surprising that everyday action control may be affected by neurological disorders. Of particular interest in this context are disorders such as ideational apraxia (IA: De Renzi *et al.*, 1968; De Renzi & Lucchelli, 1988), frontal apraxia (FA: Luria, 1966) and action disorganisation syndrome (ADS: Schwartz *et al.*, 1991, 1995, 1998, 1999), as well as disorders of action occurring with various forms of dementia (e.g., semantic dementia (Hodges *et al.*, 2000), and dementia with various aetiologies (Giovannetti *et al.*, submitted)). These disorders are not necessarily distinct. Thus, frontal apraxia and action disorganisation syndrome are generally accepted as referring to a single disorder but emphasising different aspects of that disorder (lesion site versus behavioural disturbances), and Buxbaum *et al.* (1998) and Giovannetti *et al.* (submitted) argue that all four disorders generally lead to similar patterns of breakdown in action. Regardless of the distinctness or otherwise of each of the disorders, they are of special interest because many of the errors of everyday action produced by such neurological patients can be understood as exaggerated forms of the more occasional errors produced by normal subjects. Thus, Schwartz *et al.* (1991) reported a patient with anterior corpus callosum and bilateral frontal lobe damage (HH) who frequently produced errors such as adding butter to coffee (when preparing instant coffee), and perseveratively turning the tap on and off while attempting to brush his teeth. Both of these errors may be understood as extreme forms of the kind of action slips that occur occasionally in the behaviour of normals (especially when they are distracted: Reason, 1984).

The errors of both normals and neurologically impaired individuals offer the prospect of insights into the systems and processes involved in the control of everyday action, and both have informed the development of the CS/SAS theory. However, several alternative accounts of the control of action exist, and it has been argued that the CS/SAS theory does not sit well with some impairments of everyday action control (Schwartz *et al.*, 1991). This paper surveys current theories of the control of action and considers how various forms of breakdown in action control following neural damage may be accounted for within those theories. The paper begins with a more detailed description of the CS/SAS theory before considering empirical studies of the breakdown of action control (in both naturalistic and controlled settings) and the application of the CS/SAS theory to such breakdown. Alternative accounts, of both action control and its breakdown, are then surveyed. The paper ends by drawing out from the theoretical and empirical work major themes in the control of everyday action.

Contention Scheduling and the Supervisory Attentional System

Within the dual-systems theory of Norman & Shallice (1980, 1986), the system responsible for control in routine situations, CS, is held to consist of a hierarchically structured network of action schemas. Schemas represent the abstract structure of well-learned action sequences, independent of any specific objects to which those action sequences might be applied (e.g., Schmidt, 1975). Thus, one might possess schemas for brushing one's teeth or preparing tea. Hierarchical structuring is held to arise because schemas may comprise further, component, schemas. Thus, a tea preparation schema might contain component schemas for boiling water or adding milk to a beverage. In addition, component schemas may be shared by several higher-level schemas. Thus, coffee preparation and tea preparation might share sub-schemas for boiling water and adding sweetener.

Schemas are assumed to have associated triggering conditions, activation values and selection thresholds. A schema's triggering conditions specify the conditions under which the schema should be initiated. The activation value is a continuously varying quantity that can be affected by factors such as: mutual inhibition between schemas with overlapping resource requirements; triggering from the environment (which is dependent upon the extent to which the schema's triggering conditions are matched by the environment); triggering from higher-level schemas; motivation; and direct excitation or inhibition from the SAS (the system responsible for action control in non-routine situations).

Behaviour is controlled by those schemas within CS that are most active. Specifically, if the various factors affecting a schema's activation cause that activation to exceed the schema's selection threshold, then the schema is selected and begins to actively excite its component schemas. This excitation, under normal functioning, leads to one or more component schemas also becoming active and hence selected. Selection of a schema at the lowest level triggers the corresponding low-level behaviour (e.g., grasping in an appropriate manner). Once selected, a schema continues to operate until either its goal is satisfied or its component schemas are complete, whereupon it is inhibited, allowing other schemas to become active.

The assumptions concerning activation flow are essential to the maintenance of order within the CS system. For example, the assumption of mutual inhibition between schemas with overlapping resource requirements is critical in preventing multiple schemas with conflicting resource requirements from becoming active simultaneously. Similarly, the assumption of environmental triggering of schemas is critical in ensuring the correct timing of component schemas. Such schemas are effectively primed through excitation from a higher-level selected schema. Environmental triggering then discriminates between the components. This, and inhibition of completed schemas, bias the CS system towards performing the components schemas of a selected high-level schema in the correct sequence.

Several aspects of the internal structure and functioning of CS are motivated by behavioural disturbances resulting from neurological disorders. Thus, utilisation behaviour (Lhermitte, 1983; Shallice *et al*., 1989), which involves an apparent inability by afflicted patients to avoid using objects in their immediate environment in an appropriate fashion, even when specifically instructed not to do so, suggests that action schemas may be triggered by the presence of appropriate objects in the immediate environment, but that under normal functioning such triggering is insufficient to result in object use (possibly because of inhibition from competing schemas, or because of inhibition from the SAS). Further evidence for an activation-based CS system may be adduced from amphetamine psychosis (in which subject's repetitive and stereotyped behaviour is suggestive of a hyperactive CS system: cf. Robbins & Sahakian, 1983) and Parkinson's disease (which includes among its symptoms an inability to initiate action, possibly resulting from an under-active CS system: cf. Frith, 1992). Norman & Shallice (1986) also suggest that the processes of competition within CS can account for both perseverative behaviours and distractibility of patients with frontal lesions, on the assumption that such patients' behaviour results from a normally functioning CS system in the absence of appropriate SAS control.

The primary foci of Norman & Shallice (1980, 1986) were CS and the distinction between CS and SAS. SAS itself was characterised only in abstract terms as a separate system that operated indirectly by modulating activation within CS. SAS was held to be invoked either when CS did not contain a schema for the desired behaviour or when it was necessary to avoid a strong habitual response. In such situations the effect of SAS was to excite or inhibit schemas within CS in sequence in order to obtain a desired behaviour. More recently, Shallice & Burgess (1996) have considered the internal structure and operation of SAS, and suggested that its interaction with CS is effected through the construction (by SAS) of temporary schemas. Such schemas, it is argued, control behaviour through standard CS mechanisms (i.e., by modulating activation flow to component schemas within the CS system).

The neural localisation of CS and SAS remains unclear. Norman & Shallice (1986) suggested that the functions of CS might be performed by the basal ganglia. More recent work (Rumiati *et al.,* in press), however, suggests that the motor cortex is a more likely site. Supervisory functions are generally considered to be performed by frontal structures (Shallice, 1982, 1988). Further localisation is likely to result from current attempts at fractionation of the SAS (cf. Shallice & Burgess, 1996; Burgess *et al.*, 2000). Frith (2000) suggests that the dorsolateral prefrontal cortex plays a critical role in the modulation of CS by SAS.

The CS/SAS account is rooted in earlier work by both Norman and Shallice. Shallice (1972) proposed an early information processing model of thought and action. The model was motivated by the need to provide an information processing correlate for the phenomenological concept of consciousness, and incorporated a set of competing goal-directed "action systems". Action systems were argued to have continuously variable activation values, to receive activation from perceptual or motivation systems, and to be mutually inhibitory. Norman (1981) was concerned to account for action slips and lapses in normals. He developed an activation-trigger-schema (ATS) framework, in which action was controlled by schemas that have activation values, and which could be triggered by aspects of the immediate environment. Norman used the ATS framework to provide an analysis of a range of slips and lapses. Capture errors, for example, such as counting "…, 8, 9, 10, Jack, Queen, King" when counting pages produced by a copying machine, may be explained in terms of unintentional activation, either due to recent related thoughts or activities (e.g., playing cards) or to environmental triggering. The parallels between the systems of Shallice (1972) and Norman (1981) and the CS system are clear.

Disorders of Action Control and Their Relation to Contention Scheduling

The original development of Norman & Shallice's dual-systems account of action control was not directly informed by action control disorders of the apraxic type. Nevertheless several such disorders are of direct relevance to the structure and functioning of CS and its relation with SAS. Thus, Ideational Apraxia (IA: De Renzi *et al.*, 1968; Poeck & Lehmkuhl 1980; De Renzi & Lucchelli, 1988) is characterised by impaired performance on simple tasks involving the production of a sequence of actions, typically using multiple objects. Such simple tasks, including for example pouring from a bottle into a glass and drinking from the glass, are presumably the province of CS. IA would therefore appear to be a consequence of breakdown of either CS processes, access to/storage of the information used by CS, or both. IA is generally associated with damage to the left temporo-parietal junction (De Renzi & Lucchelli, 1988), but similar behavioural signs may be shown by patients with extensive frontal lesions (i.e., frontal apraxics). Thus, Luria (1966) noted that some frontal patients were prone to error on simple tasks such as lighting a candle. His patients tended to perseverate (e.g., continuing to strike the match against the match-box after the match was lit) and misuse everyday objects through the merging of fragments of related behaviour (e.g., lighting a candle and then attempting to smoke it as if it were a cigarette).

Notwithstanding the behavioural similarities between IA and FA on simple tasks involving multiple actions, the apparent difference in localisation, together with the now standard views of the role of the frontal lobes in executive tasks (Shallice, 1982, 1988) and the role of temporo-parietal structures in action control (Jeannerod, 1997), points to a different relationship between FA and the CS/SAS complex. Specifically, FA would seem more appropriately explained as a consequence of a failure by SAS to properly regulate CS (due either to improper functioning within SAS or to improper behaviour of SAS at the SAS/CS interface). This explanation requires that some form of SAS input is necessary for normal performance on tasks as simple as lighting a candle, and brings FA under the umbrella of other frontal disturbances discussed by Norman & Shallice (1986). It is also essentially the position advocated by Luria (1966), who considered the frontal lobes to be critical to the programming, regulation, and verification of behaviour (see also Shallice, 1988), and who attributed FA to "the gross disintegration of the "preliminary synthesis" of intended actions and […] disturbances of the process of comparison of intention and effect" (Luria, 1966, p. 238).

That supervisory input may be necessary for normal performance on everyday tasks is to some extent a departure from early versions of the SAS/CS theory. However, recent data from eye-movement studies of normals completing the everyday task of tea-making (Land *et al.*, 1999) suggests that some supervisory-type processes are employed in the service of everyday action. In particular, Land *et al.* (1999) have found evidence for several different types of monitoring (locating, directing, guiding and checking) that normals engage in at key points during tea-making. Such monitoring may reflect supervisory processes that, if necessary, modulate activation flow within CS. If so, the data of Land *et al.* imply that some supervisory processes play important roles in the performance of everyday action.

The distinction between IA and FA is not undisputed. Action disorganisation on everyday tasks following frontal injury has been investigated extensively by Schwartz and colleagues, using both single case study methodology (Schwartz *et al.*, 1991, 1995) and group study methodology (Schwartz *et al.*, 1998). These studies, together with detailed comparisons between the patterns of errors produced by frontal and left-temporal patient groups on complex multiple object tasks (Buxbaum *et al.*, 1998) suggest that IA and FA (referred to by Schwartz and colleagues as Action Disorganisation Syndrome) are equivalent disorders. This is not to say that IA and FA patients are indistinguishable in their behaviours. Rather, the assertion is that they share a specific action control deficit. In the case of frontal patients, this deficit may present in conjunction with other executive functions and/or gross behavioural disturbances.

Some light may be shed on the possible relations between IA, FA and CS by considering in detail the behaviour of IA and FA patients on a variety of tasks (including several that have been used to determine the presence of IA), and by reconsidering the relation between CS and these tasks. Tasks that are intended to be diagnostic of IA are normally designed with a view to allow discrimination between IA and ideomotor apraxia (IMA). IMA affects lower-level motor control, and is apparent in tasks such as imitating gestures (e.g., saluting) and pantomiming. Thus, De Renzi & Lucchelli (1988) compared the performance of 20 right-handed patients with left brain damage on a multiple objects test (which included tasks with a sequential component such as lighting a candle and preparing a letter for posting) with their performance on three further tests: tests of object use pantomime (which required patients to pantomime the use of a range of objects, such as a hammer or a tooth-brush, which were presented visually to the patient); a test of actual object use (using the same objects from the pantomime test); and a test of gesture imitation. The patients all showed signs of IMA, but there was no correlation between their scores on the gesture imitation test and the multiple object test, suggesting that IMA and IA are distinct disorders.

Patient errors on the multiple objects test were categorised by De Renzi & Lucchelli into six types. The most frequent error type was the omission of a necessary step (e.g., attempting to fix a stamp to an envelope without first moistening the stamp). Only one patient in the group of 20, patient 12 who was least severe on most measures, made no omission errors. The number of omission errors did not, however, correlate significantly with total errors ($r = 0.357$; $p < 0.123$). In contrast, object misuse (e.g., making a stirring motion with a bottle opener inside a glass) and action mislocation (e.g. sticking the stamp on the back of the envelope), which were also common, did correlate with total errors (object misuse: $r = 0.929$; $p < 0.001$; action mislocation: $r = 0.760$; $p < 0.001$). Other errors included moderate rates of general perplexity and clumsiness and low rates of anticipatory sequence errors.

Schwartz and colleagues (Schwartz *et al.*, 1991, 1995, 1998) and Humphreys & Forde (1998; see also Forde & Humphreys, 2000) have performed similar studies of the use of multiple objects by frontal patients, including naturalistic/observational studies of everyday tasks such as preparing coffee, and more controlled experimental tasks involving an additional level of complexity (e.g., preparing and packing a lunch box, both in the absence and presence of distractor objects). Similar results were obtained, with the most frequent error type being that of omission of a step. Additionally, both Schwartz *et al.* (1998) and Humphreys & Forde (1998) found that the presence of distractor objects did not lead to inappropriate use of those objects. Schwartz *et al.* (1998) did, however, report an increase in omission errors when distractor objects were present.

On the basis of this evidence, it would appear that the patients studied by Schwartz and colleagues and by Humphreys & Forde represent an apraxic syndrome closely related to, if not indistinguishable from, that studied by De Renzi & Lucchelli (1988). In this respect it is curious to note that, although all patients in the De Renzi & Lucchelli study had left brain damage, that damage was not exclusively temporo-parietal, and five patients were described as having lesions restricted to left frontal regions. No differences were observed by De Renzi & Lucchelli between frontal and temporo-parietal patients on any of the tests. In a similar vein, Buxbaum *et al.* (1998) have reported data from group studies of frontal and left temporal patients performing complex everyday activities. No significant differences were found in the error profiles (or the sensitivity to the presence of distractor objects) between the two groups. Both of these studies thus further support the view that IA and FA are intimately related.

An alternative position that might be adopted is that multiple object tests are too coarse to discriminate between IA and FA. This position suggests that, while multiple object tests may discriminate between IMA and higher-level apraxias, further testing is required to discriminate between IA and FA. We therefore turn to a second task — picture sequencing — that has been claimed to be diagnostic of IA (Lehmkuhl & Poeck, 1981). The picture sequencing task requires subjects to order a set of photographs depicting stages in a simple sequential multiple objects task (e.g., looking up a phone number and making a phone call). Lehmkuhl & Poeck (1981) administered a set of picture sequencing tasks to several patient groups (5 IA patients, 30 non-IA patients with left brain injuries, 10 non-IA patients with right brain injuries and 15 control subjects). All five IA patients performed more poorly (producing more incorrectly sequenced photograph sets) than subjects from any of the other groups. Moreover, the IA patients were no different from the other groups on ordering pictures of everyday activities with a sequential component that did not involve multiple objects (e.g., shopping). On the basis of this study, Lehmkuhl & Poeck (1981) suggested that a deficit in the sequencing of pictures depicting simple multiple object tasks was indicative of IA.

The sequencing abilities of patients with action selection disorders potentially attributable to frontal damage have been explored by Humphreys & Forde (1998). In one experiment (experiment four), four patients (two with predominantly frontal damage and action selection disorders as revealed by behaviour on simple multiple object tests and everyday tasks and two neurologically-impaired control subjects without an action organisation deficit) were given a set of cards with verbal descriptions of steps from an everyday task (e.g., preparing toast). The descriptions had been elicited from the subjects in a previous experiment. The subjects were required to place the cards in the correct temporal sequence. All subjects made order errors, but the action-impaired subjects made many more errors than the neurological control subjects. These results are consistent with those from similar studies by Sirigu *et al.* (1995, 1996) on the sequencing of action descriptions by frontal patients. While Sirigu and colleagues did not examine performance of everyday activities in their patient groups, they did find that frontal patients were more susceptible than posterior patients or control subjects to sequence errors (and closure errors, whereby a sequence would be prematurely terminated) when ordering verbal descriptions of task steps.

In a further task, Humphreys & Forde (1998) asked the same subjects to sequence series of letters and numbers. The action-impaired subjects were particularly poor at sequencing letters, though one patient also showed difficulties with numbers. In contrast, the neurological control subjects made few errors in ordering either type of stimulus. Humphreys and Forde suggest that the sequencing deficits of frontal apraxics are most pronounced in tasks that draw upon long-term knowledge which is not intrinsic to the stimuli being sequenced.

Notwithstanding the difference in modality of presentation, the results of Lehmkuhl & Poeck (1981) and Humphreys & Forde (1998) suggest that both frontal and ideational apraxics have difficulties in sequencing the components of everyday tasks. Frontal apraxics appear in addition to show more profound sequencing difficulties (extending to seriation tasks involving numbers and/or letters). The situation is not clear cut, however. Rumiati *et al.* (in press) report two IA patients (with no frontal involvement) who were unable to perform simple sequential multiple object tasks, but who had little difficulty in sequencing corresponding photographs. Rumiati *et al.* contrast their IA patients with a frontal control patient who was able to perform the sequential multiple object tasks with few errors and could correctly sequence both numbers and shapes of different sizes, but who had difficulties in sequencing task-related photographs. Thus, contrary to Lehmkuhl & Poeck (1981), a deficit in the sequencing of photographs depicting multiple object tasks is neither necessary nor sufficient for IA.

The information processing requirements of picture sequencing and the performance of multiple object tasks are very different. They clearly have common elements (e.g., the knowledge of the components and order of the underlying script for the task) and distinct elements (e.g., those relating specifically to performing an action). The inability of (some) IA patients to perform picture sequencing has been argued to imply that such patients are unable to access that knowledge (Lehmkuhl & Poeck, 1981), but Sirigu *et al.* (1995) offer the same explanation for the inability of frontal patients to order verbal descriptions of steps within a task, and Humphreys & Forde (1988) offer a related explanation for the sequencing deficits of their (predominantly) frontal patients. However, none of these explanations can extend to Rumiati *et al.*'s frontal patient, who appears to have had intact task knowledge, despite being unable to apply that knowledge in picture sequencing.

The empirical picture is therefore unclear. On the one hand, a variety of patient groups perform in a qualitatively and quantitatively similar manner on everyday tasks involving the sequential use of multiple objects. In many cases similar results are obtained on picture/description sequencing tasks, with no clear distinction between IA and FA patients. However, some dissociations between patients on sequencing tasks have been reported: IA, at least, can occur in the absence of a sequencing deficit. At present the same cannot be said for FA.

How might the similarities between IA and FA (assuming that they are distinct) be accounted for within the Norman & Shallice (1980, 1986) dual-systems approach? It was suggested above that within such an approach IA might be characterised as a deficit within CS, while FA might be characterised as a deficit related to SAS and its control over CS. Schwartz *et al.* (1991) pointed out that such an account failed to explain why disorganisation of routine behaviour (i.e., action that could, in principle, be controlled by CS alone) could occur following damage confined to frontal regions. If the control of routine action does not require supervisory attention, then damage to supervisory processes should not impact upon that behaviour.

One counter to this argument concerns the definition of routine behaviour. The patient reported by Schwartz *et al.* (1991) was observed over a three month period in a neuropsychological recovery ward. Two "routine" behaviours were examined: preparing instant coffee (in the context of eating an institutional breakfast) and brushing teeth. In both cases, these tasks were being performed in a non-routine environment. Indeed, arguably HH's recovery over the three month period reported by Schwartz *at al.* reflects the progressive routinisation of his behaviours within the neuropsychological ward. Such routinisation would, according to the dual-systems theory, reduce the supervisory load imposed by the tasks. Similar comments apply to patient JK (Schwartz *et al.* 1995).

More recent work by Schwartz and colleagues (Schwartz *et al.*, 1998, 1999; Buxbaum *et al.*, 1997, 1998) has investigated the behaviour of various patient groups on the Multi-Level Action Task (MLAT). This task requires subjects to perform a variety of everyday subtasks within a controlled experimental environment. While it may be argued that many of the components of the subtasks are likely to be routine to some subjects (e.g., buttering bread), the higher level task in which those component tasks are embedded (e.g., packing a lunchbox), and the controlled experimental context in which the MLAT is performed, ensure that the MLAT taps a level of action beyond that which is routine.

The argument in defence of the CS/SAS account of FA is therefore that everyday action (as performed within the MLAT) must be distinguished from routine action. Everyday action requires supervisory control (a point made by Schwartz *et al.*, 1991), and hence will be impacted by deficits in that control. In contrast, routine action, by definition, does not require supervisory control, and hence need not be impacted by deficits affecting that control. In order to make this argument more strongly, it is necessary to provide concrete instances of routine tasks or actions, and to specify precisely how supervisory processes may be invoked in everyday activities. In addition, in order to relate the argument back to the claim that IA and FA are distinct disorders affecting distinct functional components of the action selection system it is necessary to demonstrate that FA does not impact performance of truly routine activities, and that different functional disorders (one relating purely to CS and the other affecting the modulation of CS by SAS) can yield equivalent behaviours on more complex tasks such as the MLAT.

A Computational Implementation of Contention Scheduling

The above issues have begun to be addressed through the computational implementation of the CS theory (Cooper & Shallice, 2000; see also Cooper *et al.*, 1995, Cooper *et al.*, submitted). Although the implementation extends the CS theory in several ways, it demonstrates that: 1) a system based on CS is capable of controlling routine action; 2) with minor extensions it is capable of controlling everyday action; and 3) breakdown of the system can lead to behaviour on everyday activities similar to that seen in both FA and IA. It remains to be demonstrated that an additional system is required for the control of non-routine action, or that in such an extended model multiple forms of damage may lead to similar breakdown of action on everyday sequential multiple object tasks.

The Model

The Cooper & Shallice (2000) implementation of the CS theory follows the Norman & Shallice (1986) description in most respects: at the centre of the model (see figure 1) is a hierarchically structured network of schemas that compete for activation within an interactive activation framework. Schemas receive excitation and inhibition from various sources, including higher level schemas, the representation of the environment and competing schemas. The principal theoretical developments embodied in the model concern the representation of the environment and the inclusion of mechanisms to regulate serial order. The model has been applied to a range of tasks, including coffee preparation (Cooper *et al.*, 1995; Cooper & Shallice, 2000), choice reaction time (Cooper, 1998) and packing a lunch box (Cooper *et al.*, submitted).

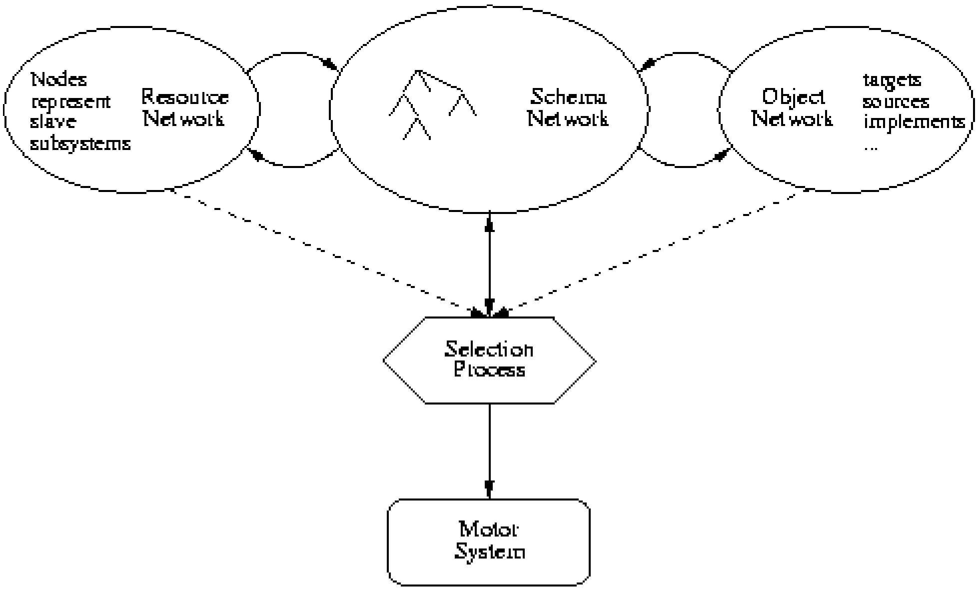

Figure 1: The principal functional components of the Contention Scheduling implementation.

The representation of the environment is modelled as a second interactive activation network, in which nodes correspond to object representations. Object representations have separate activations for different functions. Thus, a representation of, for example, a sugar bowl might be highly active as a source but inactive as a target. In such a situation an action like *dip spoon*, which requires a source into which the spoon should be dipped, will be likely to use the sugar bowl, and an action like *empty spoon*, which requires a target into which the spoon should be emptied, will be likely to use some other target. Nodes in a third interactive activation network represent cognitive and effective resources (e.g., a language processing subsystem, the hands) that might be required when performing a schema.

The object and resource representation networks interact with the schema network via feedback loops, such that object and resource representation nodes excite, and are excited by, schema nodes, provided that the corresponding objects/resources are appropriate for the corresponding schemas. This mechanism ensures that, when a schema becomes active, it will tend to excite appropriate object and resource representations on which to operate, and when an object or resource representation becomes active, it will tend to excite schemas that use it.

A selection process monitors the schema network and selects a schema when its activation exceeds its selection threshold. In order for the model to select schemas in an appropriate order, it is necessary that schemas be activated or triggered in sequence. Some low-level actions may be sequenced largely on the basis of environmental triggering. Higher order schemas (e.g., relating to making instant coffee, where most people add coffee grinds before milk/cream), however, require an additional mechanism to control sequence. This is achieved within the model by gating activation from a selected schema to its component schemas, such that only those component schemas that are appropriate at a given point in time, are activated when their parent schema is selected. In the coffee making case, excitation from the “coffee-making” schema would not pass to the “add milk” schema until the “add coffee grinds” schema was complete. This was originally achieved in a version of the model applied to the task of coffee preparation (Cooper & Shallice, 2000) through the specification of *ad hoc* ordering constraints within higher-level schemas, but a subsequent implementation applied to the more complex everyday task of preparing and packing a lunch box (Cooper *et al.*, submitted) introduced pre-conditions and post-conditions on the components of all schemas. A portion of the schema hierarchy for this more complex task, with pre-conditions and post-conditions specified, is shown in figure 2.

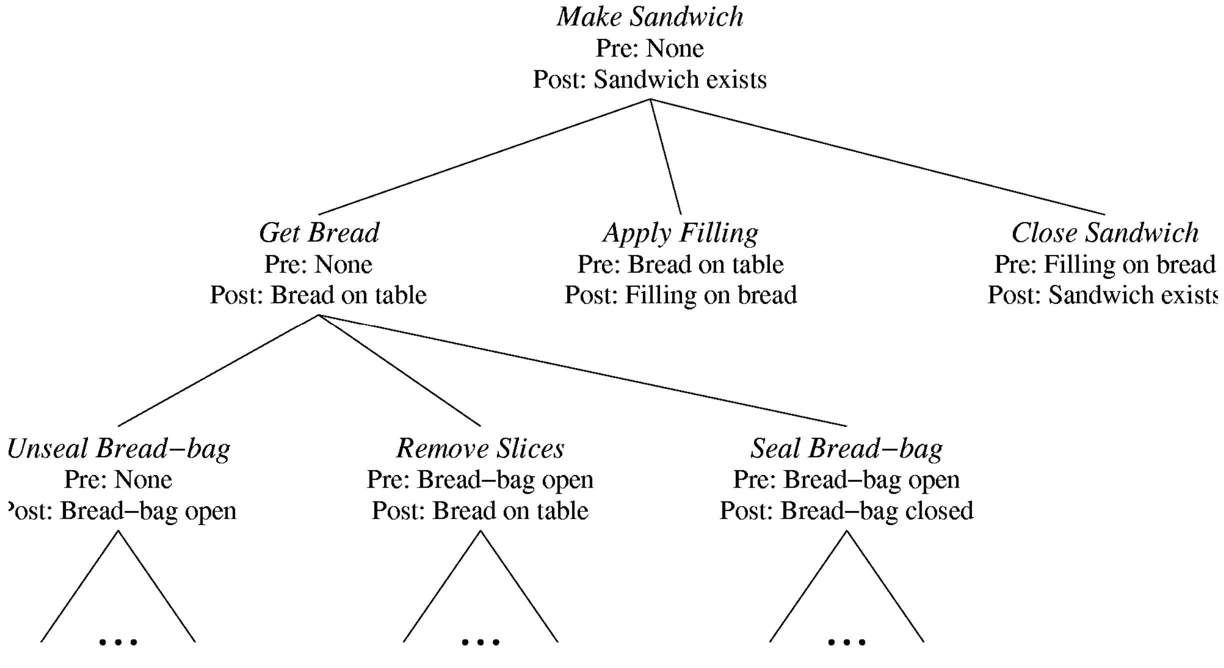

Figure 2: A portion of the Contention Scheduling schema network, with informal pre-conditions and post-conditions specified. Subschemas and their pre-conditions are not shown for *Unseal Bread-bag*, *Remove slices* and *Seal Bread-bag*.

Pre-conditions and post-conditions play an essential role in the model’s application to complex tasks. Consider the case of making a sandwich (a component of the lunch box packing task). The task requires that two slices of bread are first removed from a bread-bag. This in turn requires that the bread-bag is opened, the slices removed and then the bread-bag resealed. A pre-condition of removing the slices is that the bread-bag is open. That the bread-bag is open is also a post-condition of the opening step. If the bread-bag was left open, then, because the post-condition of opening is satisfied, the opening step will not receive excitation from its parent schema, even when that schema is selected. However, the *remove slices* schema will receive excitation from its parent schema at this stage, because its pre-condition (that the bread-bag is open) is satisfied (see figure 2). In this way, the use of pre-conditions and post-conditions allows for behavioural flexibility by providing a mechanism for component schemas to be optional. This flexibility can, in principle, apply at any level in the schema hierarchy.

Behaviour of the Model

When given an appropriate set of schemas, the model is, with suitable tuning of the strength of activation flow between the various networks, able to generate extended sequences of task-appropriate, goal-directed actions. In the case of packing a lunch box, up to 52 actions may be involved. Each action must be selected at an appropriate point in the task, and in association with appropriate object and effector representations. Noise within the interactive activation networks leads to variability in the order of subtasks, but, at low levels, does not normally lead to erroneous action selections.

The model may be lesioned either by increasing the level of noise or by altering the strength of any of the activation sources. Cooper & Shallice (2000) found, with respect to the coffee preparation task, that a decrease in top-down excitation within the schema network, coupled with an increase in environmental triggering from the object representation network, led the model to produce all of the types of errors common in frontal apraxia (e.g., sequence errors, omission errors, object substitution errors, etc.). They also found that lesioning through modification of other parameters (specifically self activation and lateral inhibition) produced behaviour reminiscent of amphetamine psychosis and Parkinsonism.

As noted above, application of the model to the more complex task of preparing and packing a lunch box required the addition of more systematic mechanisms to control sequential order. On this task, the model was generally more susceptible to omission errors but less susceptible to all other error types. The mix of error types produced by frontal apraxics was only observed at high levels of noise, where the model produced the full range of error types, with a bias towards omission errors, and was appropriately sensitive to the presence of distractor objects (producing significantly more omission errors, and more object substitution errors, in the presence of distractors than in their absence). In particular, decreasing top-down excitation within the schema network led to an increase in omission errors, but not to an accompanying increase in errors of commission (Cooper *et al.*, submitted).

The two simulations present a mixed picture. While the model is able to simulate both normal and disorganised behaviour on multiple tasks, different manipulations appear to be required to generate disorganised behaviour on different tasks. This may in part be attributed to task differences. For example, in a case study of one frontal apraxic, Schwartz *et al.* (1991) report different error profiles for different tasks, with the errors produced by the patient being dependent on the error possibilities provided by the task.

The Nature of Pre-Conditions and Post-Conditions

There are at least two ways in which the pre-conditions and post-conditions introduced for control of complex everyday activities may be interpreted. First, their goal-oriented nature may be taken to imply that they belong to the realm of supervisory processes. On this interpretation, the model is not simply a model of CS, but a model of CS with rudimentary supervisory processes. The gating of top-down excitation based on pre-conditions and post-conditions may then be re-interpreted as the net result of top-down excitation applied by a CS system to all component schemas combined with inhibition from SAS of schemas with unsatisfied pre-conditions or with satisfied post-conditions. This re-interpretation fits well with the view that frontal lobes frequently serve inhibitory functions, but suggests a different approach to the simulation of frontal damage. On this view, such damage should comprise increasing excitation of component schemas whose pre-conditions are not satisfied or whose post-conditions are satisfied.

A second interpretation of pre-conditions and post-conditions stems from the observation that, computationally, they are no more complex than triggering conditions: they are evaluations based on states of the environment. The difference is that pre-conditions and post-conditions are dependent upon the higher-order context in which a schema is triggered. From this perspective, pre-conditions and post-conditions are effectively task-specific triggering (and inhibiting) functions, and their inclusion within a low-level, unsupervised, system for routine action control may be justified.

Issues Remaining to be Addressed by the Model

Evaluation of the CS model as described is hindered by two factors: the need to explicitly specify schema structure (including pre-conditions, triggering conditions and post-conditions) on a task-by-task basis, and the absence from the model of supervisory functions such as monitoring and error recovery. Cooper & Glasspool (2001) have begun to address the first of these difficulties by demonstrating that schema triggering conditions can be acquired through reinforcement learning. However, it is the second factor that is most problematic. If CS is a system for the control of routine behaviour, then any model of CS can only be evaluated on routine behaviour, and if the action of CS may be modulated by supervisory functions such as error recovery after detection of an error (Shallice & Burgess, 1996), then both monitoring and error recovery must be modelled in order to properly simulate errorful behaviour over an extended period (as in the behaviour of frontal apraxics on the lunch box packing task). It is likely that the elaboration of the model to include supervisory processes of monitoring and error recovery will present difficulties for the model's evaluation. In this regard, eye movement data, such as that of Land *et al.*, (1999), but extended to include different neurological groups, will prove invaluable.

Alternative Accounts of Action Control and its Breakdown

The distinction between routine and non-routine action, and the subsequent introduction of separate action control systems, distinguishes the CS/SAS account of action control from most other accounts. Schwartz *et al.* (1991, 1998) suggest, however, that the distinction is not necessary in accounting for breakdown of action control in everyday activities. This section therefore surveys a number of alternative accounts of action control, with special attention to their relation to the CS/SAS theory and to the ways in which IA/FA errors may arise within the various accounts.

Roy & Square (1985)

Roy & Square (1985) propose a three level "conceptual-production system" model of limb control and consider how a number of apraxic errors may arise within the model. The highest level of the model is purely conceptual, and concerned with three types of abstract action-related knowledge: knowledge of objects in terms of actions and functions, knowledge of actions independent of objects, and serial order knowledge. The two lower levels are based on condition-action rules (productions), and concerned with knowledge of action in sensorimotor form and the mechanisms of movement control respectively. It is assumed that environmental cues may led to actions being triggered and selected, and that activation may spread between associated action control units. Furthermore, while higher levels are assumed to require greater attentional resources, simultaneous execution of multiple action programs is still assumed to be possible.

The details of action flow and its role and relation to the production system elements of the model are not spelt out. Nevertheless, Roy & Square provide a qualitative account of many apraxic errors. Thus, some object misuse errors are attributed to breakdown of conceptual knowledge, while spatial errors (e.g., attempting to write with the wrong end of a pencil) are attributed to incomplete spatial knowledge at the intermediate production system level.

Notwithstanding the under-specification of certain aspects of Roy & Square's account, there are important similarities and differences between it and the CS/SAS model. Similarities include the distinction between a high level system requiring attentional resources and lower-level systems, the activation-based nature of action control units with triggering from the environment and the possibility for multiple active action programs. Differences include the use by Roy & Square of a production system at lower levels and of spreading activation between related actions, and the use within the CS/SAS model of a distinct network of object representations. The differences between the systems lead to differences in accounts of certain apraxic-type errors, but there are still multiple ways in which a single behavioural error might be accounted for within the Roy & Square model. Thus, an object misuse error may result from faulty conceptual knowledge, or from faulty operation within the production system, or by spreading activation from one action to a related action. If one adopts the most obvious (and admittedly crude) characterisation of IA and FA in the model — that IA is primarily due to faulty conceptual knowledge and FA is primarily due to faulty spreading of activation — then, like the CS/SAS model, the Roy & Square model predicts that both apraxias may result in similar behavioural disturbances on everyday tasks.

MacKay (1985)

Roy & Square (1985) do not consider the details of how actions within a sequence are timed. This is the primary focus of the theory advanced by MacKay (1985), who also proposes an activation-based system of action control. MacKay posits three types of nodes: content nodes, sequence nodes, and timing nodes. Content nodes are arranged hierarchically, with nodes at the lowest level corresponding to muscle movements. Content nodes may receive activation from higher level content nodes, a pragmatic system (roughly equivalent to the SAS), the environmental context and/or from sequence nodes. Sequence nodes in turn receive activation from timing nodes, which determine the rate of behaviour.

There are clear similarities between MacKay's approach and the dual systems approach of Norman & Shallice. The principal difference concerns the inclusion of sequence and timing nodes. Sequence nodes represent the serial order of actions within a sequence through inhibitory links from nodes at the start of the sequence to nodes later in the sequence (cf. Estes, 1972). Thus, the sequential relationship between A, B, and C is encoded via inhibitory links from the node corresponding to A to those corresponding to B and C, and from the node corresponding to B to that corresponding to C (see figure 3). When all nodes within a sequence are activated by a timing node, that with the least number of inhibitory links will reach threshold first (i.e., A in this example, which has no inhibitory links). This node will then excite appropriate action nodes and, when the actions are completed, be inhibited, allowing the next sequence node (B, in this example) to reach threshold.

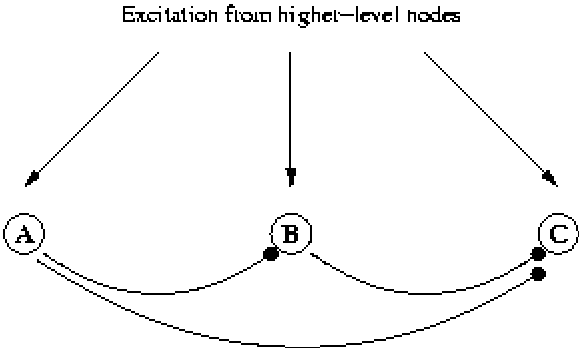

Figure 3: MacKay's (1985) inhibitory approach to sequencing.
Connections marked ———● are inhibitory.

MacKay (1985) suggests two ways in which IA/FA-type behaviour might arise within the system: as a disconnection syndrome affecting higher levels of the action system and other cognitive systems, or as a dysfunction of the sequencing nodes. The parallels between MacKay's theory and the CS/SAS approach mean that the former is equivalent to a disconnection between CS and SAS. A similar account of FA may therefore be given. IA cannot be accounted for purely via the latter, however. While a dysfunction of sequence nodes would account for sequence errors (including omissions, which may also be attributed to decay of activation, and perseveratons), it would not account for object substitution errors. MacKay suggests that such errors require impaired top-down excitation of action nodes, which, it is argued, leads to a greater dependence on environmental triggering (much as in the CS/SAS theory).

Duncan (1986)

One fact that is perhaps under-emphasised in the above discussions of frontal apraxia is the generalised nature of action disorganisation that may follow frontal lobe damage. Duncan (1986) argues that this generalised disorganisation is best conceived of as a failure of goal-based cognition, resulting either from failure to adequately compare existing states of the world with goal states, or failure to retrieve or construct actions or action sequences that are adequate for achieving one's current goals. This view is consistent with the view that one of the functions of SAS is to formulate and regulate (goal-directed) plans (Shallice, 1982). Duncan's contribution, which is concerned purely with FA, is to clarify the nature of specific subprocesses required for goal-directed behaviour. The account does not, however, address all aspects of FA. In particular it is lacking in detail with regard to the origins of specific error types, and some types of error (e.g., object substitution errors) would appear to be entirely beyond the scope of the theory.

Grafman (1989, 1995)

Grafman (1989, 1995) argues that impairments following frontal damage may be attributed to deficits in task knowledge. In order to make this argument, Grafman presents a theory of the structure and organisation of that knowledge. Specifically, he proposes that the sequence of component tasks within a higher-level task, and their approximate durations, are represented in units (which he refers to as Managerial Knowledge Units: MKUs), that behaviour is controlled by MKUs, that MKUs are stored in the prefrontal cortex, and that frontal damage therefore impacts upon the use of MKUs to control behaviour.

Managerial Knowledge Units are held to vary along (at least) two orthogonal dimensions. First, they may correspond either to high-level tasks carried out over an extended period or to low-level tasks carried out in a brief time period (or to any level in between). In this sense, MKUs range from high-level script-like or MOP-like entities (cf. Schank & Abelson, 1977; Schank, 1982) to low-level schema-like entities. Second, MKUs may vary in specificity. A specific MKU relates to a particular event or class of highly similar events (e.g., a weekday morning routine). An abstract MKU is a generalisation over a number of loosely related more specific MKUs (e.g., an abstract morning routine that generalises over weekday, weekend, and holiday morning routines). When behaviour can be appropriately controlled by a concrete MKU (i.e., in situations for which behavioural routines have been developed, such as a typical weekday morning), it is. When a situation arises for which a concrete MKU is not available (e.g., the first morning of one's retirement), behavioural control falls back upon appropriate but more abstract MKUs.

The hierarchical organisation of MKUs is similar to the organisation of schemas within Norman & Shallice's (1986) CS system, but (at least in recent versions of the theory: Grafman, 1995) that organisation is proposed to extend to high-level tasks. MKUs are also held to include entry and exit conditions (i.e., conditions under which they are normally performed, and their normal consequences). These are similar to schema pre-conditions and post-conditions in the CS model described above, but MKUs extend the concept of a schema by including temporal information concerning the approximate or normal duration of component MKUs, and information concerning the relative importance of component MKUs. This information is held to be critical in accounting for the control of behaviour in normals.

It is assumed that frontal damage results in damage to the representation or retrieval of MKUs, but that more concrete MKUs (corresponding to more routine situations) are less prone to damage. These assumptions are held to account for the sensitivity of behaviour following frontal damage to task familiarity, with behaviour on familiar or routine tasks being less impaired than behaviour on less familiar or non-routine tasks. Sirigu and colleagues have found some evidence for this position. In a script generation study comparing patients with prefrontal lesions, patients with posterior lesions and controls, Sirigu *et al.* (1995) found that frontal patients made fewer errors in generating routine scripts (e.g., getting ready for work) than non-routine scripts (e.g., taking a holiday to Mexico). All subjects produced scripts that independent judges rated as containing sequence errors, but only subjects with frontal lesions produced scripts with closure errors (i.e., scripts that terminated before or after the stated goal). Frontal patients were also impaired on determining the importance of components within the scripts that they had generated (e.g., rating taking a shower more important than leaving home when going to work). (Curiously Zalla *et al.* (2000) report similar findings concerning the rating of importance by Parkinson's Disease patients, though such patients have no difficulties in script generation, suggesting a dissociation between membership of a script and importance.) In a follow-up study Sirigu *et al.* (1996) examined the abilities of the same subjects to assemble scripts from cards describing potential script subcomponents. Frontal patients also performed poorly in this task, producing significantly more sequence errors and placing significantly more component activities in incorrect scripts.

Although Grafman (1989, 1995) does not specifically address FA, his account of the functional consequences of frontal injury suggests that FA is the result of an impairment of task knowledge. This in itself is not a radical suggestion. Grafman's contribution is more in specifying, through the concept of an MKU, what task knowledge might consist of, and arguing that a dual-systems account is not necessary to account for the behavioural disturbances of frontal patients. The account does not address specific error types (e.g., why omission errors are so common), or apraxias resulting from temporo-parietal damage.

Rothi, Ochipa & Heilman (1991)

A different level of analysis is reflected in the model of limb praxis proposed by Rothi *et al.* (1991). This model elaborates the stages of processing between various input modalities (specifically verbal, gestural and visual input) and motor output, based primarily on evidence from different forms of ideomotor apraxia and neurophysiology. It is proposed that motor control may make use of several functional subsystems, including action input and output lexicons (which contain representations of basic motor units for reception and production respectively) and an action semantics system (which contains knowledge of the purpose of actions, their organisation into sequences, and their relation to tools and objects). It is further proposed that motor output is mediated by innervatory patterns, that encode the muscle movements necessary for performing a particular action, and control movement via the motor cortex. With these subsystems in place, Rothi *et al.* (1991) argue that there are two processing routes between gestural input and motor output, namely a direct route via innervatory patterns, and an indirect route passing through the action input and output lexicons to innervatory patterns. This indirect route may also involve the action semantics system, which, in the case of visual object input, may also be activated by an object recognition system.

Although the model is primarily concerned with ideomotor apraxia, Rothi *et al.* suggest that ideational apraxia may result from selective damage to the action semantics system. Such damage would not affect object recognition, but would impact upon, for example, tool use. Notwithstanding this, the model is insufficiently specified to provide a detailed account of most error types under consideration (omissions, perseverations, etc.). As noted by Rumiati *et al.* (in press), it is also unclear how the model might account for object substitution errors.

Kimberg & Farah (1993)

A number of psychological impairments (beyond FA) are associated with frontal lobe damage. Kimberg & Farah (1993) cite four tasks that are typically performed poorly by frontal patients (motor sequencing, the Stroop task, Wisconsin card sorting, and memory for context), and provide a unified account of patient performance on these tasks in terms of a working memory impairment. The account is rooted in Goldman-Rakic's (1992) account of frontal lobe function (in which dorsolateral prefrontal cortex instantiates a form of working memory) and supported by simulations developed within the ACT-R cognitive architecture (Anderson, 1993; Anderson & Lebiere, 1998). Of particular interest in the current context is motor sequencing, for Kimberg & Farah relate this task directly to impairments on behaviour in everyday activities (and hence to FA). The motor sequencing task involves five stimuli, each with an associated response. A response is required after the presentation of each stimulus. Following this another stimulus is presented. Frontal patients are able to perform the task, but make frequent errors. Most errors are perseverative in nature, and consist of producing a correct response on one trial and then producing the same, now incorrect, response on the following trial.

ACT-R is a production system architecture in which working memory consists of a set of elements, each with its own activation value. Working memory elements are linked, such that they may activate each other. Activation is also subject to noise. The associations between stimuli and responses within the motor sequencing task are encoded as productions, which receive activation from working memory elements. Each stimulus excites elements in working memory, which then excite productions. The production that is most highly activated is the one which fires, generating a response.

The ACT-R simulation of motor sequencing is able to perform the task without error (like normals). When working memory is impaired, however, through a weakening in the connections between working memory elements, the model produces frequent errors. The error pattern is qualitatively similar to that of frontal patients, with most errors being of the perseverative type, but with non-perseverative errors also occurring. This is only weakly supportive of FA as a working memory impairment, as the type of responses possible within the task are limited (incorrect responses are necessarily either perseverative or non-perseverative), and the task abstracts most of the complexities of everyday activities. Thus, there is nothing equivalent to simultaneously selecting actions and appropriate objects, or of maintaining a high-level goal such as preparing coffee. Furthermore responses are directly triggered by the presentation of a stimulus, so the likelihood of omission errors is small.

Notwithstanding the simplicity of Kimberg & Farah's motor task, it is clear that some errors produced by FA patients might be understood in terms of impaired working memory. Omission errors, for instance, may arise through forgetting of necessary steps (or weakening of links between steps), and certain perseverative errors may arise through forgetting that a specific goal has been achieved (or weakening of the link between a goal and the representation of its result). Object substitution errors may also, with some ingenuity, be attributed to a working memory impairment. If working memory contains object representations and those representations are linked to action control units, then a reduction in the strength of those links may result in an inappropriate object representation being activated even when the correct action control unit is activated. (Such an account goes well beyond the published Kimberg & Farah model, and owes much to the approach of Cooper & Shallice (2000).)

While the preceding working memory account of different types of action error is feasible, it is unclear whether a unified account of frontal impairments is appropriate. As Kimberg & Farah note, there are dissociations among frontal tasks, with some patients performing well on some tasks and poorly on others, and *vice versa*. The effects of frontal damage cannot therefore be understood in terms of a general working memory impairment, as this fails to account for the diversity of observed deficits. If a working memory account of frontal behaviour is to be given, this diversity requires, at minimum, that patients with different behavioural deficits have different working memory impairments. One could speculate that such differences might arise from weakening of different types of links, but such speculation goes beyond the model of Kimberg & Farah, and undermines the claim that frontal impairments result from a general working memory deficit.

There are several substantive differences between the working memory impairment account of FA and one based on a loosening of control between SAS and CS. First, Kimberg & Farah's account is based on the use of a general purpose cognitive system (working memory), rather than a special purpose action control system (CS).

One consequence of this is that the working memory impairment account predicts interference between tasks requiring a memory load and non-routine action (cf. Schwartz, *et al.*, 1998; Humphreys *et al.*, 2000). Second, Kimberg & Farah (1993) argue that the dual systems approach of CS and SAS is unnecessary, and that isolated damage to supervisory processes cannot account for the behaviour of frontal patients on simple motor sequencing tasks or for the failure of such patients on memory for context tasks. However, the sufficiency of a single-system approach is not demonstrated by Kimberg & Farah. Critically they fail to show that tasks on which frontal patients perform well (e.g., standard tests of IQ) are not affected by working memory impairments. In addition the claim that motor sequencing does not require supervisory attention is open to debate: motor sequencing tasks may require the creation (by SAS) of a temporary schema to guide behaviour.

Schwartz, Buxbaum et al. (1998, 1999)

Perhaps the most extensive behavioural studies of disorders of everyday action following brain damage have been conducted by Schwartz, Buxbaum and colleagues (Schwartz, *et al.* 1991, 1995, 1998, 1999; Buxbaum *et al.*, 1997, 1998). Recent studies (see especially Buxbaum *et al.*, 1998) have shown strong behavioural similarities between IA and FA, as well as an apparent continuum of severity. Schwartz *et al.* (1998) argue that these results, and in particular effects of task complexity and the absence/presence of distractor objects (as described above), cannot be accounted for within either a working memory deficit account of action selection (such as that of Kimberg & Farah, 1993) or a supervisory failure account of action selection (such as that proposed by Shallice, 1988). Schwartz, Buxbaum and colleagues propose instead that the organisation of action requires some kind of cognitive resource, and that disorganisation of action as seen in FA is a consequence of diminished availability of this resource in impaired individuals.

Evaluation of this proposal requires an elaboration of the notion of cognitive resource, together with a theory of how cognitive resources might be consumed by the processes of action organisation. Cooper *et al.* (submitted) have simulated key aspects of the data on which the resource theory is founded, and these simulations may be used to clarify the above issues. The simulations are based on the application of an extension of the Cooper & Shallice (2000) model of contention scheduling to the task of packing a lunchbox: one of the tasks used by Schwartz *et al.* to examine the organisation and breakdown of action control in normals and several patient groups. As noted above, the crucial extensions to the model involve the representation within the schema hierarchy of schema pre-conditions and post-conditions, which were used to regulate the excitation of component schemas by selected high-level schemas. Also as noted above, the model arguably blurs the distinction between CS and SAS by including such mechanisms. Nevertheless the extended model is able to account for normal behaviour on the task, and, via the addition of noise, for 1) the pattern of errors produced by neurological patients (with omission errors being most frequent, and substitution and sequence errors also occurring but at lesser rates) and 2) the sensitivity of such patients to distractor objects (leading to more omission and substitution errors).

Schwartz *et al.* (1998) suggest that the effect of a reduction in availability of cognitive resources may be reduced availability of excitation within a hierarchically structured activation-based schema network. Cooper *et al.* (submitted) further suggest that one effect of this reduction in excitation is to magnify the effects of noise inherent in the system. Hence the reduction in excitation may be modelled as an increase in noise. The blurring of the distinction between CS and SAS inherent in the approach is also consistent with the single-systems position advocated by Schwartz *et al.* (1991).

Humphreys & Forde (1998)

Case studies of the control of everyday action have also been reported by Humphreys & Forde (1998), who find support for the distinction between CS and SAS and the internal composition of CS in terms of a hierarchically structured activation-based schema control system. Humphreys & Forde note, however, a double dissociation between two forms of perseverative disorganisation exhibited by their frontal apraxic patients. Both patients produced perseverative errors on everyday tasks (such as cutting wrapping paper while wrapping a present), but in one case these perseverative errors were of the continuous type (involving immediate repetition of an action) and in the other they were of the recurrent type (involving returning to a previous action after an interval). Both types of perseveration have previously been observed in the disorganised behaviour of frontal patients (cf. Schwartz *et al.*, 1991), but the double dissociation suggests either that in normal behaviour different mechanisms are responsible for preventing the different forms of perseveration, or that a single mechanism is involved but that that mechanism can break down in different ways.

In order to account for the different forms of perseverative error Humphreys and Forde (1998) propose that the sequencing of components within a schema is controlled by a process of competitive queuing (cf. Houghton, 1990; Burgess & Hitch, 1992; Shallice *et al.*, 1995; Glasspool, 1998). Nodes within the competitive queuing mechanism receive activation from control units which varies with time. The strength of this activation on any node depends on the desired position of that node within the sequence. Nodes earlier in the sequence initially receive greater excitation from the control nodes, but once a node is selected (and its corresponding action performed) it is inhibited. In addition, as steps in the sequence are performed the activation gradient from the control nodes changes to bias nodes later in the sequence (see figure 4). In normal functioning this inhibition prevents a node from being reselected and allows subsequent nodes to become active. Humphreys & Forde (1998) suggest that continuous perseveration may result from a failure of the inhibitory process, whereas recurrent perseveration may result from faulty operation of the control signal.

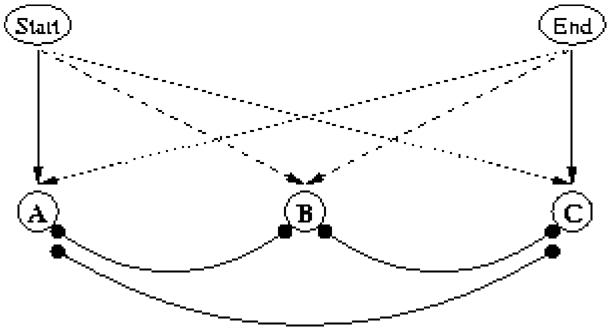

Figure 4: A competitive queuing architecture for action control.
Control nodes are those labelled "Start" and "End".
Connections marked ●——● are mutually inhibitory.
Adapted from Humphreys et al. (2000).

The introduction of sequence control nodes differentiates the proposal from the Cooper & Shallice (2000) model and leads to a system with some similarity to that of MacKay (1985). The competitive queuing approach also has much to commend it with regard to the learning of action sequences (a clear deficiency in the Cooper & Shallice model). However, it is unclear that different forms of failure are required to generate different types of perseveration within a competitive queuing approach. In particular, the dynamics of competitive queuing require that schema nodes are strongly inhibited upon deselection. If this inhibition is slightly too weak, a schema node may gradually recover and eventually be inappropriately reselected. This corresponds to the case of recurrent perseveration. If inhibition is very weak, it may be insufficient to prevent a schema node from being immediately (and inappropriately) reselected. This corresponds to the case of continuous perseveration. Thus, different forms of perseveration may arise from a single mechanism with different levels of impairment. This suggests a slightly different account of recurrent perseveration than that given by Humphreys & Forde (1998), but does not undermine the basic competitive queuing approach.

It is also relevant to note that the double dissociation between types of perseveration is consistent with the Cooper & Shallice model. Within that model, continuous perseveration will arise if inhibition following completion of a schema is insufficient. Recurrent perseveration requires a different mechanism: decay of information concerning goal achievement.

Humphreys, Forde & Francis (2000)

While Humphreys & Forde (1998) accept a division between routine and non-routine action control systems, they question the division in later work (Humphreys *et al.*, 2000), where they report an experiment in which errorful performance was induced in the everyday actions of normal controls by loading working memory with a secondary task (the "Trails Test", in which participants are given a letter/number pair, e.g., E3, and required to continue the sequence with successive pairs, e.g., F4, G5, etc.). Errors on the Trails Test were generally self-corrected, but most errors on the everyday tasks arose immediately after an error on the Trails Test. Humphreys *et al.* (2000) interpret the results in terms of working memory failure (in a way analogous to Kimberg & Farah, 1993), and suggest that the role of working memory in everyday action is in maintaining goal representations, and that the role of goal representations is to provide an appropriate activation gradient across action nodes within a competitive queuing system.

Botvinick & Plaut (2000)

A common feature of most of the above accounts of action control is the assumption of a hierarchically structured representation of action schemas. In addition, many of the accounts (MacKay, 1985; Humphreys &

Forde, 1998, Cooper & Shallice, 2000) assume an underlying system of interactive activation, in which nodes corresponding to action schemas have activation values that are affected by various influences, and selection of an action schema is determined by the schema's activation value. Botvinick & Plaut (2000) reject both of these assumptions, and present instead a recurrent network model (cf. Elman, 1990) in which action is triggered by a distributed (non-hierarchically structured) internal representation of task context, with that context being a function of the current state of the environment and the context at the previous stage of processing. Action units in the model correspond to basic level actions (e.g., pick up, pour, put down), as in the model of contention scheduling described above, but there are no nodes corresponding to higher-lever action schemas, and there is no competition between action nodes. The only input to action nodes comes from the representation of task context (see figure 5).

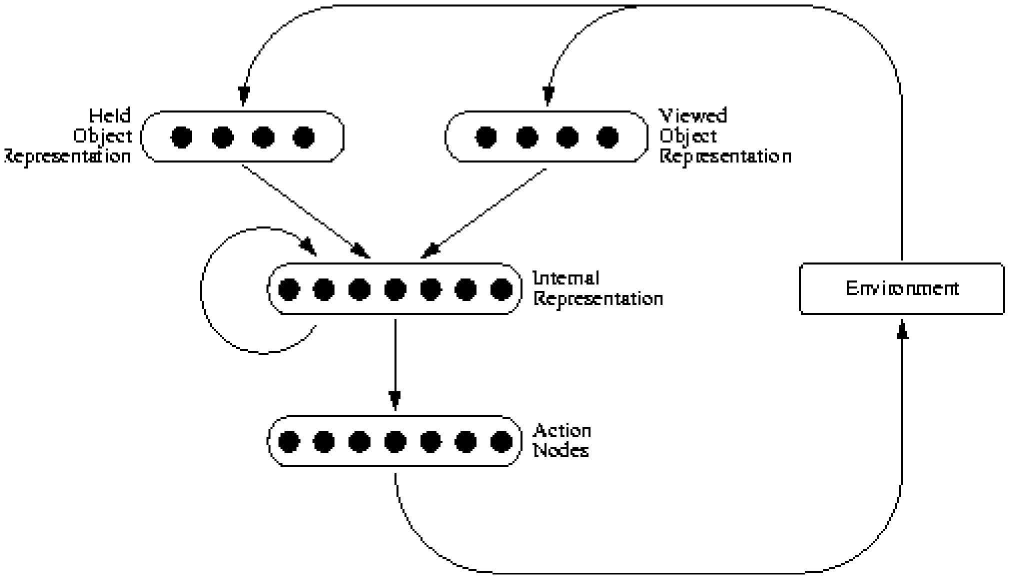

Figure 5: A recurrent network architecture for sequential action control.
Adapted from Botvinick & Plaut (2000).

Task knowledge within the model is embodied in connection weights between the input environment representation, the context representation, and the action nodes. One implication of the embodiment of task knowledge in this way is that knowledge of the components of a sequence and knowledge of their position in that sequence cannot be dissociated. Hence the model predicts, in apparent conflict with the results of Sirigu *et al.* (1995, 1996), that order and content of sequential behaviour cannot be independently impaired.

As in most recurrent network models, task knowledge is acquired through supervised learning. That is, the model is presented with a series of input/output pairs (both in isolation and in sequence), and weights are modified according to now well-established procedures such that the model's output for any combination of input and context comes to more closely resemble the required output. Botvinick & Plaut (2000) demonstrate that, after training, the model is able to successfully perform everyday tasks such as preparing tea and coffee. Within the model these tasks involve completing 35 to 40 actions in sequence and with appropriate objects. The basic approach is considerably simpler than each of the approaches sketched above, and, although it is unclear how the model might account for behaviours suggestive of an activation-based substrate (e.g., Parkinson's disease and amphetamine psychosis — see also Lashley, 1951), it nevertheless demonstrates that many of the complexities in more traditional approaches (e.g., hierarchical structuring, goal-dependent excitation and inhibition after completing a schema) may not be necessary for an account of routine action selection. In addition, the inclusion of a learning mechanism addresses a clear deficiency of the Cooper & Shallice (2000) model. (Though see Cooper & Glasspool (2001) for preliminary results on the learning of schema triggering conditions.)

Action slips and lapses and frontal apraxia may both be simulated in the Botvinick & Plaut model by adding noise to the representation of context. Small amounts of noise lead to occasional errors similar to those catalogued by Norman (1981) and Reason (1979, 1984). When noise is greater, errors are more extreme, and may include instances of all types observed in frontal apraxic patients. Perhaps surprisingly the model can produce object substitution errors (even though it has no separate representation of objects) and both continuous and recurrent forms of perseveration. It is unclear, however, if recurrent and continuous perseveration may dissociate within the model in the way observed by Humphreys & Forde (1998).

Botvinick & Plaut (2000) do not discuss the application of their model to the simulation of ideational apraxia. One may nevertheless speculate on how other forms of damage may affect the model's behaviour. In particular, errors of tool use are likely to result from the addition of noise to the input representation of the environment, but it is unclear how (or even if) such damage might impact upon sequential behaviour. Further simulations are necessary.

Several other issues remain to be addressed by Botvinick & Plaut. Of particular importance is the intended relation between the model and supervisory processes, which is unclear. Action within the model is initiated by the input of a representation corresponding to a task instruction, such as whether tea or coffee should be prepared. Such instructions are equivalent to high-level schemas in hierarchical models. It is unclear if Botvinick & Plaut subscribe to a dual-systems approach, but it is not incompatible with the model to assume that supervisory processes may generate representations of task instructions and use them to trigger the system into performing the corresponding action sequence. It is even compatible to assume that representations corresponding to action sequences of different levels of complexity (e.g., preparing coffee as well as its subtasks) may be generated by a supervisory system, and that a single, well-trained, model may be able to respond appropriately to both high-level and lower-level task instructions. Such extensions would appear to be necessary if the model is to be applied with different levels of supervisory control, or if it is to be re-configured part-way through a task to correct an error.

General Discussion: Emergent Issues

The above theories differ in a variety of ways. The principal differences point to four key issues concerning the control of everyday action and its breakdown following neurological damage.

Action Control: One System or Two?

Debates have arisen in several areas of cognitive psychology concerning the existence or otherwise of multiple systems (e.g., reading: Seidenberg & McClelland (1989) versus Coltheart *et al.* (1993); inflectional morphology: MacWhiney & Leinbach (19891) versus Marcus *et al.* (1995); object semantics: Shallice (1987) versus Riddoch *et al.*, 1988). Arguably, action control should be added to this list. While the CS/SAS theory is accepted by many, the distinction between two qualitatively distinct forms of action control has been questioned by Grafman (1995) and Schwartz, Buxbaum and colleagues (Schwartz, *et al.* 1998, 1999; Buxbaum *et al.*, 1998; Giovannetti *et al.*, submitted). Separable systems are also not implicated in Kimberg & Farah's (1993) working memory deficit view of frontal apraxia, and Humphreys *et al.* (2000) suggest that the errors of control subjects in their dual-task paradigm are best accounted for by a failure to maintain goal state information within a single system, rather than by a dual-systems view. Parsimony also favours a single-system approach.

However, Humphreys *et al.* (2000) do provide an alternative account of their data in which the everyday task is controlled by a separate system that is prone to error, but that is monitored by another (presumably executive) process. This is entirely consistent with the dual-system view, and with the fractionation of supervisory processes proposed by Shallice & Burgess (1996). Two criticisms of this alternative account — concerning the error-prone nature of the routine system and the need for the error monitor to have its own model of correct task performance — are easily met by recalling that everyday tasks are not necessarily routine tasks, and by noting that if supervisory processes are able to control basic-level action when necessary, then those processes must have access to a model of correct task performance. The dual-systems view also receives independent support from engineering approaches to the construction of autonomous agents, which have found separate systems for the control of routine behaviours and for the construction and subsequent execution of plans in non-routine situations to be highly desirable, if not necessary (Shallice, 1988; see also Glasspool, 2000).

There is also some debate about the cognitive reality of schemas (or similar task knowledge structures) and their hierarchical structuring. Explicit hierarchical structuring is apparent in the approaches of Norman & Shallice (1980, 1986), Roy & Square (1985), MacKay (1985) and Grafman (1989, 1995), but hierarchical structuring is absent from the proposal of Humphreys *et al.* (2000), and in the recurrent network model of Botvinick & Plaut (2000) schemas play no causal role — they are merely emergent regularities over trajectories in a multi-dimensional activation space.

Frontal Apraxia and Ideational Apraxia: One Disorder or Two?

Frontal Apraxia and Ideational Apraxia are traditionally viewed as distinct disorders that affect everyday action. They differ at least in the localisation of neural damage and in the other behavioural disturbances that tend to be associated with the disorders. On the CS/SAS approach to action control, the disorders are clearly distinct: Ideational Apraxia is a disorder of CS and Frontal Apraxia is a disorder of SAS affecting its control over CS. However, the results of group studies by Schwartz, Buxbaum and colleagues (especially Buxbaum *et al.*, 1998) have raised the possibility that the distinction between the disorders is not well founded. The absence of any effect of patient type on error profile in their Multi-Level Action Task, together with the continuity of error profile across severity of deficit, has been taken by Schwartz, Buxbaum and colleagues as indicating that everyday action disorganisation in these patient groups is a consequence of a single underlying deficit. While it is possible that these results reflect group study methodology applied to patients with "impure" deficits, single case studies of IA and FA, showing double dissociations in, for example, error profiles on everyday tasks, remain to be reported.

Sequential Control: Interactive Activation or Recurrent Activation?

Most (well-specified) accounts of action control are based on an underlying activation-based system in which nodes corresponding to actions receive both triggering activation from a representation of the environment and context activation from some representation of the task. These sources of excitation combine to yield one active action representation, which is then performed.

There are two basic variations on this theme: interactive activation, in which schema nodes are discrete entities that excite and inhibit each other, and recurrent activation, where schemas are not explicitly represented and where task context is represented in a distributed connectionist fashion. Of the approaches based on interactive activation, each is founded on a different computational mechanism for sequential control. Thus, Roy & Square (1985) suggest that sequence is controlled through a system of production rules, MacKay (1985) proposes separate sequence nodes in which order arises from inhibition of later nodes by earlier nodes, Humphreys & Forde (1998) suggest a system based on competitive queuing, and Cooper & Shallice (2000) suggest ordering constraints that gate top-down excitation of component schema nodes.

Botvinick & Plaut's (2000) recurrent activation model stands out against this backdrop of interactive activation approaches. The Botvinick & Plaut approach demonstrates that some action selection errors, previously thought to be characteristic of an underlying interactive activation mechanism, may arise from a recurrent system. However, several questions remain to be addressed by the approach. Most notably, the relation between the recurrent system and supervisory processes such as error correction remains unspecified.

Breakdown of Action Control: A Disorder of Knowledge or Control?

One issue implicit in the above survey of theories of action control and its breakdown concerns the relation between knowledge and the use of that knowledge in the control of action. The existence of object substitution errors would appear to suggest that breakdown of knowledge relating to object use or to object-action associations may be a contributing factor in FA, and some forms of action control breakdown may plausibly be attributed to loss of such knowledge (e.g., semantic dementia: Hodges, *et al.*, 2000). Some consensus is emerging, however, that FA may be attributed not to loss of task knowledge but to failure to appropriately use task knowledge. Thus, Humphreys & Forde (1998) note one frontal apraxic prone to perseverative errors who, when cutting wrapping paper in order to wrap a present, stated that the paper was not big enough, but continued to cut the paper into smaller and smaller pieces. In this instance the patient's deficit would appear to be in his control of action (and an inability to inhibit his ongoing activities) rather than in his knowledge. This view is further supported by the presentation by Forde & Humphreys (2000) of an FA patient who, despite no loss of object semantic knowledge, was still prone to object substitution errors. The ability of the frontal apraxics of Rumiati *et al.* (in press) to sequence pictures of activities that they could not perform correctly likewise suggests an impairment in performance and not competence. This is consistent with the results of Sirigu *et al.* (1995, 1996), who found that frontal patients were able to generate descriptions of the components of on everyday task, but were impaired on sequencing those components, and echoed in the contention scheduling model (Cooper & Shallice, 2000), where action disorganisation results from an impairment to activation propagation within the hierarchical control mechanism rather than to schema knowledge, the cognitive resource theory of Schwartz, Buxbaum and colleagues (Schwartz *et al.*, 1998; Buxbaum *et al.*, 1998; Giovannetti *et al.*, submitted), and the competitive queuing model proposed by Humphreys *et al.* (2000), in which action disorganisation is attributed to a failure to maintain appropriate excitation of goal structures in working memory (and the consequent loss of an appropriate activation gradient within a competitive queuing action sequencing system).

The one account of everyday action disorganisation that contrasts with this consensus is that of Botvinick & Plaut (2000). This model makes no clear distinction between knowledge and control. As such, breakdown of the model cannot unambiguously be attributed to a breakdown in either component.

Conclusion

Breakdown in the control of everyday action may arise following a variety of neurological disorders. While such breakdown has informed theories of the control of action, disagreement remains over the answers to fundamental questions. On the empirical side, recent work has shown that omission errors are common in the behaviour of both frontal apraxics and ideational apraxics, and that both patient groups are less susceptible to utilisation errors than had previously been thought. There is also converging evidence that, at least in the case of frontal apraxia, the disorder is a disorder of control and the use of knowledge, rather than a disorder of knowledge *per se*. However, the status of frontal apraxia and ideational apraxia as resulting from distinct functional disorders has been questioned. On the theoretical side, the issue has arisen of whether separable systems exist for the control of routine and non-routine activities, and, if so, what role the non-routine action control system plays in the control of everyday (as opposed to routine) activities. On the computational side, there is substantial debate over the control mechanisms underlying sequential behaviour. Recent implementation work has resulted in a better understanding of some candidate mechanisms, but has not helped to discriminate between them. In part, this may be attributed to difficulties in simulating action over extended periods, when that action may be modulated by high-level, willed, cognitive processes. Addressing these difficulties should lead to significant progress in our understanding of the control of everyday action.

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References

Anderson, J.R. (1993). *Rules of the Mind*. Lawrence Erlbaum Associates. Hillsdale, NJ.

Anderson, J.R. & Lebiere, C. (1998). *The Atomic Components of Thought*. Lawrence Erlbaum Associates, Mahwah, NJ.

Botvinick, M., & Plaut, D. (2000). Doing without schema hierarchies: A recurrent connectionist approach to routine sequential action and its pathologies. Poster presented at Cognitive Neuroscience Conference.

Burgess, P.W., Veitch, E., de Lacy Costello, A. & Shallice, T. (2000). The cognitive and neuroanatomical correlates of multitasking. *Neuropsychologia*, *38*, 848–863.

Burgess, N., & Hitch, G.J. (1992). Toward a network model of the articulatory loop. *Journal of Memory and Language*, *31*, 429–460.

Buxbaum, L.J., Schwartz, M.F., & Crew, T.G. (1997). The Role of Semantic Memory in Object Use. *Cognitive Neuropsychology*, *14*, 219–254.

Buxbaum, L.J., Schwartz, M.F., & Montgomery, M.W. (1998). Ideational Apraxia and naturalistic action. *Cognitive Neuropsychology*, *15*, 617–643.

Coltheart, M., Curtis, B., Atkins, P. & Haller, M. (1993). Models of reading aloud: Dual-route and parallel distributed processing approaches. *Psychological Review*, *100*, 589–608.

Cooper, R. (1998). Visual dominance and the control of action. In Gernsbacher, M.A. & Derry, S.J. (eds.), Proceedings of the 20th Annual Conference of the Cognitive Science Society, pp. 250–255. Madison, WI, USA. Cognitive Science Society Incorporated.

Cooper, R., & Glasspool, D.W. (2001). Learning action affordances and action schemas. In R. French & J. Sougne (eds.) *Connectionist Models of Learning, Development and Evolution*. (Proceedings of the *6th Neural Computation in Psychology Workshop*). Springer-Verlag.

Cooper, R., Schwartz, M.F., Yule, P., Warrick, S., & Shallice, T. (submitted). The simulation of action disorganisation in complex activities of daily living.

Cooper, R., & Shallice, T. (2000). Contention Scheduling and the control of routine activities. *Cognitive Neuropsychology, 17*, 297–338.

Cooper, R., Shallice, T., & Farringdon, J. (1995). Symbolic and continuous processes in the automatic selection of action. In J. Hallam (ed.) *Hybrid Problems, Hybrid Solutions*. IOS Press, Amsterdam.

De Renzi, E., & Lucchelli, F. (1988). Ideational Apraxia. *Brain*, *111*, 1173–1185.

De Renzi, E., Pieczuro, A., & Vignolo, A. (1968). Ideational Apraxia: a quantitative study. *Neuropsychologia*, *6*, 41–52.

Duncan, J. (1986). Disorganisation of behaviour after frontal lobe damage. *Cognitive Neuropsychology, 3*, 271–290.

Estes, W.K. (1972). An associative basis for coding and organization in memory. In A.W. Melton & E. Martin (eds.) *Coding Processes in Human Memory*. pp. 161–190. V.H. Winston and Sons. Washington DC.

Elman, J.L. (1990). Finding structure in time. *Cognitive Science*, *14*, 179–211.

Forde, E.M.E., & Humphreys, G.W. (2000). The role of semantic knowledge and working memory in everyday tasks. *Brain and Cognition*, *44*, 214–252.

Frith, C.D. (1992). *The Cognitive Neuropsychology of Schizophrenia*. Psychology Press, Hove, UK.

Frith, C.D. (2000). The role of dorsolateral prefrontal cortex in the selection of action, as revealed by functional imaging. In Monsell, S., & Driver, J. (eds.) *Attention and Performance, XVIII*. MIT Press, Cambridge, MA.

Giovannetti, T., Libon, D.J., Buxbaum, L.J., & Schwartz, M.F. (submitted). Naturalistic action impairments in dementia.

Glasspool, D.W. (1998). *Modelling Serial Order in Behaviour: Studies of Spelling*. PhD thesis. Department of Psychology, University College London.

Glasspool, D.W. (2000). The integration and control of behaviour: Insights from neuroscience and AI. AISB Symposium: *How to design a functional mind*. Birmingham. April.

Goldman-Rakic, P.S. (1992). Working memory and the mind. *Scientific American*, *267*, 110–117.

Grafman, J. (1989). Plans, actions, and mental sets: Managerial Knowledge Units in the frontal lobes. In Perecman, E. (ed.), *Integrating theory and practice in neuropsychology*. Lawrence Erlbaum Associates, Hillsdale, NJ.

Grafman, J. (1995). Similarities and distinctions among current models of prefrontal cortical functions. *Annals of the New York Academy of Sciences*, *769*, 337–368.

Hodges, J.R., Bozeat, S., Lambon Ralph, M.A., Patterson, K., & Spatt, J. (2000). The role of conceptual knowledge in object use: Evidence from semantic dementia. *Brain*, *123*, 1913–1925.

Houghton, G. (1990). The problem of serial order: A neural network model of sequence learning and recall. In Dale, R., Mellish, C., & Zock, M. (eds.), *Current Research in Natural Language Generation*. Ch. 11, pp. 287–319. Academic Press, London, UK.

Humphreys, G.W., & Forde, E.M.E. (1998). Disordered action schema and action disorganisation syndrome. *Cognitive Neuropsychology*, *15*, 771–811.

Humphreys, G.W., Forde, E.M.E., & Francis, D. (2000). The organisation of sequential actions. In Monsell, S., & Driver, J. (eds.) *Attention and Performance, XVIII*. MIT Press, Cambridge, MA.

Jeannerod, M. (1997). *The Cognitive Neuroscience of Action*. Basil Blackwell, Oxford, UK.

Kimberg, D.Y. & Farah, M.J. (1993). A unified account of cognitive impairments following frontal lobe damage: The role of working memory in complex, organized behavior. *Journal of Experimental Psychology: General*, *112*, 411–428.

Land, M., Mennie, N., & Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. *Perception*, *28*, 1311–1328.

Lashley, K. (1951). The problem of serial order in behavior. In Jeffress, L.A. (ed.), *Cerebral Mechanisms in Behavior*. pp 112–136. Wiley, New York, NY.

Lehmkuhl, G. & Poeck, K. (1981). A disturbance in the conceptual organization of actions in patients with ideational apraxia. *Cortex*, *17*, 153–158.

Lhermitte, F. (1983). Utilisation behaviour and its relation to lesions of the frontal lobes. *Brain, 106*, 237–255.

Luria, A.R. (1966). *Higher Cortical Functions in Man.* London: Tavistock.

MacKay, D.G. (1985). A theory of the representation, organisation and timing of action with implications for sequencing disorders. In E.A. Roy (ed.) *Neuropsychological studies of apraxia and related disorders.* North Holland, Amsterdam.

MacWhiney, B. & Leinbach, J. (1991). Implementations are not conceptualisations: revising the verb learning model. *Cognition*, *40*, 121–157.

Marcus, G., Brinkman, U., Clahsen, H., Wiese, R., Woest, A., & Pinker, S. (1995). German inflection: The exception that proves the rule. *Cognitive Psychology*, *29*, 189–256.

Norman, D.A. (1981). Categorization of action slips. *Psychological Review, 88*, 1–15.

Norman, D.A., & Shallice, T. (1980). *Attention to action: Willed and automatic control of behavior*. Chip report 99, University of California, San Diego.

Norman, D.A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In Davidson, R., Schwartz, G., & Shapiro, D. (ed.), *Consciousness and Self Regulation: Advances in Research and Theory, Volume 4*, pp. 1–18. Plenum, New York, NY.

Poeck, K, & Lehmkuhl, G. (1980). Ideatory apraxia in a left-handed patient with right-sided brain lesion. *Cortex*, *16*, 273–287.

Reason, J.T. (1979). Actions not as planned: The price of automatization In Underwood, G., & Stevens, R. (ed.), *Aspects of Consciousness*, ch. 4, pp. 67–89. Academic Press, London, UK.

Reason, J.T. (1984). Lapses of attention in everyday life In Parasuraman, W., & Davies, R. (ed.), *Varieties of Attention*, ch. 14, pp. 515–549. Academic Press, Orlando, FL.

Reason, J.T. (1990). *Human Error*. Cambridge University Press, Cambridge, UK.

Riddoch, M.J., Humphreys, G.W., Coltheart, M. & Funnell, E. (1988). Semantic systems of system? Neuropsychological evidence re-examined. *Cognitive Neuropsychology*, *5*, 3–25.

Rothi, L.J.G., Ochipa, C., & Heilman, K.M. (1991). A cognitive neuropsychological model of limb praxis. *Cognitive Neuropsychology*, *8*, 443–458.

Robbins, T.W. & Sahakian, B.J. (1983). Behavioural effects of psychomotor stimulant drugs: Clinical and neuropsychological implications. In Creese, I. (ed.), *Stimulants: Neurochemical, behavioural and clinical perspectives*, pp. 301–338. Raven Press, New York, NY.

Roy, E.A., & Square, P.A. (1985). Common considerations in the study of limb, verbal and oral apraxia. In E.A. Roy (ed.) *Neuropsychological studies of apraxia and related disorders.* North Holland, Amsterdam.

Rumiati, R., Zanini, S., Vorano, L., & Shallice, T. (in press). A form of Ideational Apraxia as a selective deficit of contention scheduling. *Cognitive Neuropsychology*.

Schank, R.C. (1982). *Dynamic Memory*. Cambridge University Press, Cambridge, UK.

Schank, R.C. & Abelson, R. (1977). *Scripts, Plans, Goals and Understanding*. Lawrence Erlbaum Associates. Hillsdale, NJ.

Schmidt, R.A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82*, 225–260.

Schwartz, M.F., Buxbaum, L.J., Montgomery, M.W., Fitzpatrick-De Salme, E.J., Hart, T., Ferraro, M., Lee, S.S. & Coslett, H.B. (1999). Naturalistic action production following right hemisphere stroke. *Neuropsychologia, 37,* 51–66.

Schwartz, M.F., Montgomery, M.W., Buxbaum, L.J., Lee, S.S., Carew, T.G., Coslett, H.B., Ferraro, M., Fitzpatrick-De Salme, E.J., Hart, T., & Mayer, N.H. (1998). Naturalistic action impairment in Closed Head Injury. *Neuropsychology, 12*, 13–28.

Schwartz, M.F., Montgomery, M.W., Fitzpatrick-De Salme, E.J., Ochipa, C., Coslett, H.B., & Mayer, N.H. (1995). Analysis of a disorder of everyday action. *Cognitive Neuropsychology, 12*, 863–892.

Schwartz, M.F., Reed, E.S., Montgomery, M.W., Palmer, C., & Mayer, N.H. (1991). The quantitative description of action disorganisation after brain damage: A Case Study. *Cognitive Neuropsychology, 8*, 381–414.

Seidenberg, M.S. & McClelland, J.L. (1989). A distributed developmental model of word recognition and naming. *Psychological Review*, *96*, 523–568.

Shallice, T. (1972). Dual functions of consciousness. *Psychological Review*, *79,* 383–393.

Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society*, *B298*, 199–209.

Shallice, T. (1987). Impairments of semantic processing: Multiple dissociations. In Coltheart, M., Sartori, G., & Job, R. (eds.) *The Cognitive Neuropsychology of Language*. pp. 111–127. Lawrence Erlbaum Associates. London.

Shallice, T. (1988). *From Neuropsychology to Mental Structure*. Cambridge University Press, Cambridge, UK.

Shallice, T., & Burgess, P.W. (1996). The domain of supervisory processes and temporal organisation of behaviour. *Philosophical Transactions of the Royal Society of London, B351,* 1405–1412.

Shallice, T., Burgess, P.W., Schon, F., & Baxter, D.M. (1989). The origins of utilisation behaviour. *Brain, 112*, 1587–1598.

Shallice, T., Glasspool, D.W., & Houghton. G. (1995). Can neuropsychological evidence inform connectionist modelling? Analyses of spelling. *Language and Cognitive Processes*, *10*, 195–225.

Sirigu, A., Zalla, T., Pillon, B., Grafman, J., Agid, Y., & Dubois, B. (1995). Selective impairments of managerial knowledge following pre-frontal cortex damage. *Cortex*, *31*, 301–316.

Sirigu, A., Zalla, T., Pillon, B., Grafman, J., Agid, Y., & Dubois, B. (1996). Encoding of sequence and boundaries of scripts following prefrontal lesions. *Cortex*, *32*, 297–310.

Zalla, T., Sirigu, A., Pillon, B., Dubois, B., Agid, Y., & Grafman, J. (2000). How patients with Parkinson's Disease retrieve and manage cognitive event knowledge. *Cortex*, *36*, 163–179.