The Simulation of Action Disorganisation in Complex Activities of Daily Living

Richard P. Cooper, Myrna F. Schwartz, Peter Yule & Tim Shallice

Action selection in everyday goal-directed tasks of moderate complexity is known to be subject to breakdown following extensive frontal brain injury. A model of action selection in such tasks is presented and used to explore three hypotheses concerning the origins of action disorganisation: that it is a consequence of reduced top-down excitation within a hierarchical action schema network coupled with increased bottom-up triggering of schemas from environmental sources, that it is a more general disturbance of schema activation modelled by excessive noise in the schema network, and that it results from a general disturbance of the triggering of schemas by object representations. Results suggest that the action disorganisation syndrome is best accounted for by a general disturbance to schema activation, while altering the balance between top-down and bottom-up activation provides an account of a related disorder – utilisation behaviour. It is further suggested that ideational apraxia (which may result from lesions to left temporoparietal areas and which has similar behavioural consequences to action disorganisation syndrome on tasks of moderate complexity) is a consequence of a generalised disturbance of the triggering of schemas by object representations. Several predictions regarding differences between action disorganisation syndrome and ideational apraxia that follow from this interpretation are detailed.

1 Introduction

Much human behaviour involves performing common tasks such as those relating to eating, dressing and commuting. Such activities of daily living (ADL) generally require little overt planning or problem solving, as is evidenced by the fact that it is frequently possible to complete a secondary task (e.g., holding a conversation) while engaged in the ADL. At the same time diary studies have shown that ADL are subject to occasional slips and lapses (e.g., Reason, 1979; Norman, 1981). Thus, after using milk to prepare a beverage one might unintentionally place the beverage, instead of the milk, in the refrigerator. Neurologically healthy individuals generally notice action lapses such as these, and spontaneously correct them.

More severe disturbances in the execution of ADL may occur following brain injury. Luria (1966) noted that patients with extensive frontal lesions were prone to errors of action in simple tasks involving multiple steps and multiple objects. Luria reported patients who, when asked to light a candle, produced errors included perseverations (e.g., continuing to strike a match after it had been lit), object substitution errors (snapping the candle in two and discarding it after it had been lit, as if it were the match) and the "blending" of action sequences (e.g., attempting to "smoke" a candle after it had been lit). Many subsequent studies have highlighted the role of frontal involvement in "action disorganisation syndrome" (e.g., Duncan, 1986; Schwartz *et al.*, 1991; Schwartz, *et al.*, 1995; Sirigu, *et al.*, 1996; Schwartz, *et al.*, 1998; Humphreys & Forde, 1998). Thus, Schwartz *et al.* (1991) reported a patient with extensive bilateral frontal lesions who, when preparing coffee in a naturalistic setting, made errors such as putting breakfast cereal in the coffee mug (an object substitution error) and attempting to pour from the cream container before opening it (an anticipation/omission error).

Working in a rather different tradition, research on so-called "ideational apraxia" (IA: Pick, 1905; Liepmann, 1920) has used "multiple object tasks" (De Renzi & Lucchelli, 1988) involving operations such as opening a can of soup with a can-opener or lighting a candle with a match. When performing such tasks, patients with left hemisphere lesions have been found to make errors including omission of component actions, misuse of objects, errors of sequence, mislocation of actions and general clumsiness (e.g., Poeck & Lehmkuhl, 1980; De Renzi & Lucchelli, 1988; Rumiati *et al.*, 2001). Thus, when lighting a candle IA patients have been reported to fail to strike the match (action omission), bring the lit match to the candlestick rather than the candle (action mislocation), strike the match at the wrong end (object misuse), and strike the match before inserting the candle into the candlestick (sequence error). De Renzi & Lucchelli (1988) argued from behavioural evidence that IA was distinct from ideomotor apraxia and from neuroanatomical evidence that "the [left] temporoparietal junction represents the most frequent but not the unique anatomical correlate of IA" (p. 1183). They suggested that the basic deficit was a result of "lack of access to a specific aspect of the semantic store" (p. 1183), although classical ideational apraxia has also been attributed to a conceptual disturbance of the sequential organisation of actions (Poeck & Lehmkuhl, 1980) and a processing breakdown in top-down excitation within a hierarchically structured interactive activation action control mechanism (Rumiati *et al*., 2001).

Impairments of naturalistic action have also been observed in other patient groups. Schwartz *et al.* (1999), for example, presented data on the disorganisation of naturalistic action in a group of 30 patients with right hemisphere lesions, including at least five whose lesions did not appear to extend into the frontal lobes, and Giovannetti *et al.* (2002) presented data from a group of 51 patients with mild to moderate dementia arising from various etiologies. Similar types of errors, including sequence errors, omission errors, action additions, and object substitution errors, were observed in both studies.

Notwithstanding other differences between patient groups, there are striking similarities between the types of errors made by frontal patients as reported by Luria (1996) and Schwartz *et al.* (1991), those made by left temporoparietal patients as reported by De Renzi & Lucchelli (1988) and Rumiati *et al*. (2001), and those made by other patient groups. Indeed, Buxbaum *et al.* (1998: see also Giovannetti *et al*, 2002) demonstrated quantitative similarities between the error profiles of the various patient groups. On a range of semi-naturalistic ADL-type tasks (including making toast, wrapping a present, and preparing a packed lunch box), patients with lesions resulting from closed head injury primarily affecting frontal regions (CHI), left cardio-vascular accidents (LCVA), right cardio-vascular accidents (RCVA), and dementia of various aetiologies were all found to be most prone to omission errors. Sequence errors, including anticipation errors, perseverations, and action reversals, were the second most common error type in all groups.

The similarities in the error profiles of different patient groups may be interpreted either as indicating a common functional deficit in the control of everyday activities (e.g., Schwartz *et al.*, 1998; 1999; Giovannetti *et al.,* 2002) or as indicating that the action control system is susceptible to a variety of different functional impairments which result in similar behavioural breakdown on semi-naturalistic ADL-type tasks (e.g., Buxbaum *et al.*, 1998; Schwartz, 1995). The latter is also consistent with the variety of theoretical accounts of deficits in the control of everyday action that have been proposed within the various traditions.

As noted above, De Renzi & Lucchelli (1988) attributed the action deficit of left temporoparietal patients to an access deficit: that part of the semantic store of object-related actions was hypothesised to be inaccessible in the course of everyday action. In contrast, Luria attributed the action deficit of patients with extensive frontal lesions 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). Information processing theories of action selection suggest several further possible accounts of deficits in the control of everyday action following brain lesions. Norman & Shallice (1980, 1986), for example, proposed a dual-systems account of the control of thought and action. One system, contention scheduling, was held to be responsible for the control of routine behaviour. This system was argued to consist of a hierarchically structured network of action schemas, where an action schema represented the components of an action sequence in terms of other (lower-level) schemas or basic actions. Action schemas were held to compete for selection within an interactive activation network, with selected schemas exciting their component schemas and ultimately controlling action. It was proposed that action schemas would only be available within contention scheduling for routine situations. In non-routine situations, the functioning of contention scheduling would be modulated by a second system, supervisory attention. Supervisory attention was argued to be a function of the frontal lobes (Shallice, 1988).

On the Norman & Shallice (1980, 1986) account, the behaviour of patients with extensive frontal lesions was suggested to result from the contention scheduling system functioning in the absence of adequate supervisory control (Shallice, 1988). However, Schwartz *et al.* (1991) pointed out that this could not account for the disorganised behaviour of frontal patients on routine tasks, as normal functioning within such tasks should not require supervisory attention. Schwartz *et al.* (1991) proposed an alternative account based on the action disorganisation of their (predominantly frontal) patient, HH, namely that action was controlled by a single system of the same general form as the contention scheduling system of Norman & Shallice (1980, 1986), but without a distinction between routine and non-routine behaviours, and where disorganisation arose from an imbalance between top-down or intentional control from schemas to their component schemas and bottom-up or environmental triggering of schemas from the immediate environment.

Computational work has demonstrated that the Schwartz *et al.* (1991) view is consistent with the types of error that occur in the disorganised action of the various patient groups on everyday tasks (Cooper & Shallice, 2000), but there are a number of alternative theories of frontal function and dysfunction which may also be consistent with observed cases of action disorganisation. In fact, the Norman & Shallice (1980, 1986) dual-systems account of behavioural control is itself consistent with several of these theories. For example, Luria's view of action disorganisation in frontal patients may be incorporated by accepting monitoring (i.e., processes involved in "the comparison of intention and effect") as a component of supervisory attention (cf. Shallice, 1988; Shallice & Burgess, 1996).

Other theories of frontal function stress the role of the frontal lobes in the storage and activation of "managerial knowledge units" to control behaviour over time (Grafman, 1989, 1995), in the on-line maintenance of representations in "working memory" (Goldman-Rakic, 1992; Kimberg & Farah, 1993), or in the inhibition of inappropriate or undesirable behaviours (Fuster, 1997). The first of these, with a single hierarchical system for action control, is related to that outlined by Schwartz *et al.* (1991). The remaining two are broadly consistent with the Norman & Shallice account. Thus, Shallice & Burgess (1996) posit a mechanism within the supervisory system for the temporary elicitation of schemas without environmental support. Such schemas are held to govern supervised behaviour by modulation of the contention scheduling system; it is also assumed that they must be maintained in the supervisory system throughout their operation to ensure adequate behavioural control. Action disorganisation could result from failure to maintain temporary schemas, in keeping with the working memory view. (Again parallels may be drawn with Luria's view by equating temporary schemas with the "preliminary synthesis of intended actions".)

The computational implementation of contention scheduling (Cooper & Shallice, 2000) facilitates the comparison of the above accounts of everyday action control and the various hypotheses concerning its breakdown following neural damage. However, the initial computational work was limited in scope – applying to the relative simple everyday task of preparing a mug of instant coffee – and provided only qualitative results. The purpose of this paper is therefore to extend the Cooper & Shallice (2000) model to more complex everyday tasks, to determine if the extended model is able to provide quantitative fits to the error patterns of the various patient groups, and to investigate the predictions of several theories of frontal breakdown and action disorganisation within the extended model.

The remainder of the paper begins with a review and reanalysis of data gathered by Schwartz *et al.* (1998, 1999), Buxbaum *et al.* (1998), Humphreys & Forde (1998) and Forde & Humphreys (2002). The extended model is then presented, together with its relation to the earlier model of Cooper & Shallice (2000). We demonstrate that the revised model can account for normal behaviour on the task of preparing and packing a lunchbox and evaluate three competing hypotheses concerning the origins of action disorganisation. The first, reduced top-down excitation within the schema hierarchy, derives from previous work concerning the relation between the CS/SAS theory and action disorganisation, both in patients (Schwartz *et al.*, 1991) and the earlier version of the model (Cooper & Shallice, 2000). The second, increased noise disrupting the flow of activation within the schema network, is considered because neurological evidence suggests that action disorganisation can result from generalised, rather than localised, damage. A number of previous models in a range of domains (e.g., Hinton & Shallice, 1991; Plaut & Shallice, 1993; Houghton, Glasspool & Shallice, 1994; Plaut, McClelland, Seidenberg & Patterson, 1996; Rapp & Goldrick, 2000; Botvinick & Plaut, 2004) have employed increased noise to model general effects of brain damage. Here it is used to model a generalised deficit within one functional subcomponent of the model – the schema network. A third hypothesis, a general disturbance of object representations, is also considered because of the close relationship between schemas and object representations within the model.

To foreshadow, the conclusions are that action disorganisation as seen in frontal patients is best accounted for by a general disturbance to schema activation, while altering the balance between top-down and bottom-up sources of schema activation provides an account of utilisation behaviour (Lhermitte, 1983; Shallice *et al.*, 1989; Boccardi *et al.*, 2002), a distinct disorder arising from bilateral medial frontal lesions. From a behavioural perspective, ideational apraxia might also be accounted for by a general disturbance of schema activation, but simulation results suggest an alternative that is consistent with both behavioural and neuroanatomical evidence – that ideational apraxia might result from a generalised disturbance of the triggering of schemas by object representations. Several predictions that follow from this alternative are discussed.

2 Action Disorganisation Syndrome: Key Empirical Findings

The studies of Schwartz, Buxbaum and colleagues and Humphreys and Forde have isolated a number of key empirical findings against which theoretical and computational accounts of action disorganisation may be evaluated. In very broad terms, errors of action may be subdivided into errors of omission (i.e., errors resulting from failing to initiate some task-essential action or sequence of actions) and errors of commission (i.e., errors resulting from initiating an action that is in some way incorrect or inappropriate). Commission errors may be further subdivided into sequence errors (where correct actions are performed but in incorrect sequential order); object substitutions (where an inappropriate object is used in place of an available appropriate object); and action additions (where extraneous unrelated actions are introduced into an ongoing activity). Sequence errors may themselves be further decomposed into anticipation/omission errors (performing $action_2$ before $action_1$ and subsequently omitting $action_1$ when $action_1$ should have preceded $action_2$), reversal errors (performing two consecutive actions in reverse order), and perseverations (repeating an action or action sequence once its goal has been achieved). This taxonomy is summarised with examples from the task of packing a lunch box (as used by Schwartz and colleagues, and as described below) in Table 1.

Table 1: Summary of error taxonomy. Examples are drawn from the task of preparing a sandwich, snack and drink and packing the three items into a lunch box, as used with various patient groups by Schwartz *et al.* (1998, 1999) and Buxbaum *et al.* (1998).

Error Type	*Examples*
Step omission	Failure to pack cookies, sandwich or drink into the lunch box Failure to include filling when making the sandwich
Sequence: Anticipation/Omission	Packing the sandwich without first wrapping it in foil Attempting to pour from the juice jar without first opening it
Sequence: Reversal	Packing the cookies or sandwich and then wrapping them Placing cookies or sandwich on foil before tearing foil from roll
Sequence: Perseveration	Taking more than two slices of bread for the sandwich Wrapping the cookies or sandwich more than once
Object substitution	Packing the lunch items into the schoolbag instead of the lunch box Using apple sauce instead of mustard on the sandwich
Action addition	Eating the sandwich or the cookies Packing inappropriate items (e.g., the mustard jar) into the lunch box

Patients additionally produce errors of manner or quality, such as using excessive quantities of ingredients, failing to use tools, or using appropriate tools inappropriately. These errors were relatively rare in the groups observed by Schwartz and colleagues, and we do not discuss them further here.

2.1 The relative proportions of error types

Schwartz *et al.* (1998) found that the most common type of error produced by their CHI patients was that of the omission of a step. Such errors accounted for 38% of all errors. Sequence errors were the second most frequent error type accounting for an additional 20% of errors. Humphreys & Forde (1998) found a similar tendency towards omission and sequence errors. They observed 34% omissions errors and 40% sequence errors in their case studies of two patients with extensive frontal lesions (averaging over their experiments 2a and 2b).[1] In both studies the two other principal error types, object substitution and action addition errors, accounted for approximately 10% of errors each.

Different tasks offer different possibilities for error, and it is possible that the relative proportions of errors of patients reflect an effect of task rather than an effect of damage to the mechanisms involved in action selection. Schwartz *et al.* (1998) explored this possibility by converting error frequencies to standardised error scores. A patient's standardised error score for any type of error is defined as the total number of errors of that type produced on a task, divided by the total number of opportunities provided by the task for that error type, multiplied by 100. Thus, a standardised omission error score of 4, for example, would result if a patient were to make 4 omission errors per 100 opportunities. Figure 1, adapted from Schwartz *et al.* (1998), shows the standardised scores for omission, sequence and object substitution errors produced by their 30 CHI patients. The preponderance of omission errors is clear, and while the relative proportion of sequence errors is reduced, such errors remain second most frequent.

INSERT FIGURE 1 HERE

Further studies by Schwartz, Buxbaum and colleagues on other patient groups have demonstrated similar error profiles. Buxbaum *et al.* (1998), for example, found 44% omission errors and 27% sequence errors in the error corpus produced by 16 LCVA patients performing a set of ADL tasks, and Schwartz *et al.* (1999) found 47% omission errors and 19% sequence errors in a comparable corpus of errors derived from 30 RCVA patients. These data, together with that of Schwartz *et al.* (1998) and Humphreys and Forde (1998), suggest that the system or systems responsible for the control of ADL-type tasks is/are particularly prone to omission errors, with sequence errors second most frequent, and object substitution errors and action additions possible but less likely.

2.2 The relative proportions of commission and omission errors as a function of severity

Schwartz *et al.* (1998) noted that omission errors were particularly common in the behaviour of their more severe patients (where severity was defined in terms of the total error score across a range of everyday tasks under a variety of conditions). This is clear from Figure 1, but the effect is also present in the errors of LCVA and RCVA patients. Table 2, which is based on a reanalysis of the data reported by Schwartz *et al.* (1998, 1999) and Buxbaum *et al.* (1998) quantifies the effect. The table shows the mean total standardised error scores and the mean "standardised commission proportion" for low and high error producers for each patient group. The standardised commission proportion for a patient is defined as the fraction of standardised commission errors to total standardised errors. The data in the table are derived from each patient performing two of three ADL tasks (preparing and packing a lunch box, preparing toast with jam, and wrapping a gift), one with just the items needed for the task, and one with additional "distractor" items available while completing the task. Patients who produced no errors are excluded from the analysis. The mean standardised commission proportion for all three patient groups is significantly higher for low error producers than for high error producers ($t(13) = 4.2$, $p < 0.001$, $t(12) = 17.9$, $p < 0.001$, $t(22) = 5.7$, $p < 0.001$ for the CHI, LCVA and RCVA samples respectively). In other words, in all patient groups low error producers tended to produce more commission errors, while high error producers tended to produce more omission errors.

[1] More than half of the sequence errors observed by Humphreys & Forde (1998) were perseverations, but such errors were rare in the Schwartz *et al.* (1998) study. Further differences between the patient profiles in the two studies are noted below.

Table 2. The standardised error rates and standardised commission proportions for three patient groups. The data are grouped according to a median split on total error scores. Patients who produced no errors were excluded from the analysis.

Group	*N*	*Mean standardised omission errors*	*Mean standardised commission errors*	*Mean total standardised errors*	*Mean standardised commission proportion*
CHI low E	8	2.357	3.148	5.506	0.801
CHI high E	7	27.119	4.966	32.085	0.180
LCVA low E	7	0.000	2.365	2.365	1.000
LCVA high E	7	23.857	3.199	27.057	0.136
RCVA low E	12	3.122	3.434	6.555	0.808
RCVA high E	12	39.315	6.846	46.160	0.186

2.3 Accomplishment and its correlation with the principal error types

Schwartz *et al.* (1998) also scored behaviour on a single accomplishment dimension that reflected the percentage of subtasks of the ADL that each participant completed, ignoring errors along the way. For example, the task or preparing and packing a lunch box (as described below) involved six subtasks. A participant who successfully completed five out of the six subtasks would obtain an accomplishment score of 83.3%. Unsurprisingly there was a strong negative correlation between total error score and accomplishment ($r = -0.918$, $p < 0.001$). However, there was also a strong negative correlation between the number of commission errors and accomplishment score ($r = -0.771$, $p < 0.001$). Thus, CHI patients with low accomplishment scores also tended to produce more errors of commission than CHI patients with higher accomplishment scores.

2.4 The effects of distractor objects

Schwartz, Buxbaum and colleagues also investigated the effect of the absence or presence of distractor objects on ADL performance. In one condition participants were required to complete an ADL task while seated at a desk with all and only those items required for the task present on the desk. In a second condition, participants were supplied with several additional items that were not needed for the task (e.g., a spatula as well as a butter knife). There was no significant effect of the presence of distractors on total errors in CHI, LCVA and RCVA populations. However, when error types were analysed separately and corrected to account for differential opportunities across tasks and conditions, all populations showed a trend towards more omission errors and more object substitutions in the presence of distractor objects. Furthermore, when the data from the three groups were analysed as one, the increase in omissions was significant. The trend towards more object substitutions remained, but did not reach significance.[2] This pattern of results was not predicted (either from existing theory or from existing models). In particular, while some theoretical positions might suggest that the presence of distractor objects should lead to an increase in object substitution errors, the observed increase in omission errors was surprising.

Further replication of the distractor effect is desirable. Two case studies (patients FK and HG) reported by Humphreys & Forde (1998) showed no overall effect of distractors on total error rates. While it is possible that this may be due to the small sample size (two) of Humphreys & Forde (1988), it may equally reflect a different pattern of impairment in the Humphreys and Forde patients. Weight is added to this latter interpretation by the fact that many of the errors produced by the patients of Humphreys & Forde (1998) were of the perseverative type, while few such errors were observed in the group studies of Schwartz, Buxbaum and colleagues.

[2]However, a group study of patients with progressive dementia, which employed the methods and materials of the Schwartz group, did find a significant increase in substitution errors in the condition with distractors (Giovannetti *et al.*, 2002).

3 A Model of Action Selection in Complex Activities of Daily Living

The above empirical findings provide a set of phenomena against which models of action selection in ADL and accounts of ADL action selection deficits may be evaluated. Two models have been published – the implementation of contention scheduling within an interactive activation framework by Cooper & Shallice (2000; see also Cooper *et al*. 1995) and the recurrent connectionist model of Botvinick & Plaut (2002, 2004). Both of these models address only simple ADL with relatively few subtasks. Thus, the coffee preparation task modelled by Cooper & Shallice (2000) and subsequently used by Botvinick & Plaut involved three subtasks (adding sugar, milk and coffee grounds to a mug of boiling water) and 12 actions. This section describes an extended version of the Cooper & Shallice (2000) model, its relation to the original model, and its application to a more complex ADL task, that of preparing a packed lunch. The task is more complex than the coffee preparation task because a) it requires many more basic actions (approximately 60 compared to 12); b) the hierarchical structuring between the top-most schema and its basic-level component schemas is substantially greater (involving up to five levels compared to three); c) the constraints governing ordering of sub-tasks are more complex (the complete task as encoded within the model comprises seven subtasks in which different elements are prepared and packed, and interleaving of some subtasks is possible); and d) it offers the possibility of running subtasks together (e.g., preparing and then packing a drink, without relinquishing control of the drink container between subtasks).

3.1 The basic level

We assume that there exist control units corresponding to “basic-level” action schemas such as *pick up*, *put down*, *open*, *close*, etc., and that these control units or nodes compete within an interactive activation network according to standard principles (e.g., McClelland, 1992). Thus, nodes have associated activation levels that are influenced by self excitation and lateral inhibition. Self influence encourages nodes to become active, while lateral influence from “competing” nodes acts against self influence. The net effect of these influences is that only one node from any subset of competing nodes may be highly active at a time. Competition within the basic-level is restricted to nodes corresponding to schemas that have overlapping resource requirements, where resources include special purpose processing subsystems (e.g., relating to linguistic or visuospatial processing) and effectors. This ensures that nodes corresponding to schemas that share such requirements cannot become active simultaneously. Thus, two nodes corresponding to basic-level schemas that both require use of the hands cannot be active at the same time, though two nodes corresponding to schemas requiring different resources (e.g., manual and vocal resources) may. Competition is normalised so that the total lateral inhibition on a node is divided by the number of competitors of that node. Consequently, schemas with many competitors are not at a disadvantage compared with schemas with few competitors.

It is also assumed that a similar network exists for object representations, with nodes in the object representation network corresponding to the objects present in the immediate environment. Nodes within the object representation network afford actions by triggering or exciting nodes within the schema network, and *vice versa*. Thus, a small portable object in view may lead to triggering of the node for the basic-level *pick up* action schema. Links between the object representation network and the schema network are bi-directional and symmetric, so the object representation node for a small portable object in view will also be triggered or excited by that for the basic-level *pick up* schema. In principle, other influences (e.g., from the supervisory attentional system) may act upon nodes in the object representation network, but we do not consider such influences in the current model.

Actions corresponding to basic level schemas may involve multiple objects. Thus, pouring involves use of one object as a source and another object as a target. We therefore assume that there are distinct object representation networks for distinct functional roles (e.g., source, target, implement, theme). We also assume that resources (e.g., the hand to use to effect an action) are allocated through a further interactive activation network, whose nodes correspond to available resources. The application of the model described here does not involve use of resources beyond two hands. We therefore do not consider this network in further detail.

Action selection occurs when a schema node's activation exceeds the selection threshold, which is a parameter of the model. This may occur because of the effects of competition, excitation from the object representation network, and/or through top-down excitation from source schemas (as described below). The action corresponding to the selected schema node (e.g., pick up) is then performed, with the object on which it is performed determined by the functional role specified by the schema (e.g., source or target) and the activation of nodes in the relevant object representation network, and the effector(s) used to perform the action determined by the requirements of the action (whether a free hand or a full hand is required) and the activation of nodes in the resource/effector network. Once an action has been performed, its corresponding schema node is inhibited, allowing other schema nodes to become active through the dynamics of interactive activation.

The interaction between the schema network and the object representation network begins to provide an account for simple utilisation behaviours (Lhermitte, 1983; Shallice *et al.*, 1989). There is positive feedback between the two networks and if this goes unchecked it may lead to an object representation node and a corresponding schema node becoming highly active. Selection will then result in the corresponding action being applied to the object. Because object representations trigger only those schemas that are appropriate to them (and *vice versa*), the action performed will be an object-appropriate one.

3.2 The schema hierarchy

The basic-level system as described in the previous section is able to perform sequences of action through successive activation of schema nodes. However, it lacks high-level organisation in its action. In order to provide for such organisation we assume that the schema network also includes control nodes for higher level schemas corresponding to partially ordered sets of lower level and basic-level action schema nodes. The network may include, for example, a node for the control of an intermediate level act such as capping a thermos flask, comprising nodes for picking up two objects (a thermos and its corresponding cup), clipping the cup onto the thermos, and putting down the capped thermos. Similarly, the network may include higher level action schemas (such as preparing a sandwich), which comprise multiple intermediate level schemas.[3] High level schema nodes may, like basic-level schema nodes, activate, and be activated by, object representation nodes.

The addition of hierarchical structure in the model is motivated in part by the existence of such structure within and between many tasks. Thus, it is natural to describe the first step of tea-preparation as boiling the kettle, and the first step of boiling the kettle as checking the water level in the kettle. In addition the subtask of boiling the kettle is shared with a number of drink-related tasks (e.g., preparing instant coffee and instant soup). Hierarchical structuring is also an integral part of the original verbal specification of the contention scheduling theory (Norman & Shallice, 1980, 1986), and receives empirical support from the nature of errors in action disorganisation (which include omission and repetition of entire subtasks: Schwartz *et al.*, 1991). The cost of hierarchical structuring, however, is the requirement for mechanisms controlling competition, selection and deselection of high-level schemas, and for mechanisms controlling the sequencing of component schemas within high-level schemas.

We assume that two high level schemas compete if and only if they share component schemas and one is not a component (or sub-component) of the other. This definition (which is simpler than that of Cooper & Shallice, 2000) is a restatement of that proposed by Norman & Shallice (1980, 1986). In addition, we assume that selection of high-level schemas parallels that of low-level schemas: high-

[3]As in the original model, schemas are goal directed and specify a set of subgoals, rather than a set of sub-schemas. The distinction only plays a role when multiple schemas co-exist for a single goal, as for the goal of opening a container, which may be achieved by different schemas depending on the type of container. Such schemas compete, with competition normally being resolved through activation from the representation of the environment. Thus, in the case of opening a container, schema selection will be determined by bottom-up factors (the type of container that is actually held) rather than top-down expectations (the type of container that should be held given the task). See Cooper & Shallice (2000) for additional details.

level schemas are selected when the activation of their control nodes exceeds the selection threshold. Following Norman & Shallice (1980, 1986), high level schemas are deselected when their activation is exceeded by that of a competitor.

To illustrate, Figure 2 shows the activation of various task-relevant schemas during completion of an ADL – pouring a drink into a thermos and sealing the thermos. Time is represented on the horizontal axis. The hierarchical structuring within the schema network leads to "temporal nesting" of activation profiles (cf. Dehaene & Changeux, 1997), whereby component schemas are activated, selected and deselected within a temporal window defined by the selection of their higher-level parent schema.

INSERT FIGURE 2 HERE

It is assumed that supervisory processes may directly excite or inhibit schemas at any point in the hierarchy. Sufficient excitation will result in selection of a high level schema. Selected schemas excite their component schemas, which may also become selected and excite their component schemas. Activation may therefore flow in a top-down manner within the schema network. Ultimately this activation flow and selection bottoms-out at the basic level, an action is performed, and the selected basic-level schema is inhibited, allowing further actions to be performed. If the action results in the goal of a higher-level schema being achieved, then the higher-level schema is also inhibited, allowing another (competing) schema at the higher level to become active and be selected.

When a schema is selected it does not necessarily excite all of its component schemas. Such excitation would not guarantee task-appropriate temporal ordering of component schemas. Instead, excitation of component schemas is gated by pre-conditions and post-conditions. Specifically, a component schema node only receives excitation from a selected parent schema node if its pre-condition is satisfied by the representation of the state of the environment and its post-condition is not. A final inhibitory mechanism acts upon a selected schema's node when the post-conditions of all of its component schemas have been satisfied. This inhibits the selected schema node until the node is deselected. Together, these mechanisms provide the system with substantial flexibility. If, for example, a component schema's post-conditions are satisfied by a fortuitous state of the task environment (e.g., if the someone has left the milk open) then the component schema will not receive top-down excitation (and action will proceed without attempting to open the already opened milk container).

3.3 Object binding

The model as described to this point is capable of much if not all of the behavioural flexibility required when performing sequential ADL of significant complexity. Neuropsychological evidence suggests, however, a further refinement. On one occasion when preparing instant coffee patient HH (reported in Schwartz *et al.*, 1991) carried out the entire task using the cereal bowl, rather than the coffee mug, as the destination for the coffee ingredients. The most parsimonious account of HH's behaviour is that he made one object substitution error in mis-identifying the destination for coffee preparation, rather than one object substitution error each time an ingredient was added to the destination.

This analysis suggests that objects may be bound to functional roles at high levels in the schema hierarchy, and not just at the basic level. It is therefore assumed that when an object representation is selected to fill an argument role of an action corresponding to a basic-level schema the object representation may also be bound to a functional role specified by a higher-level schema. This form of object binding ensures coherence of actions within high-level schemas. To illustrate, a high level schema for *make sandwich* may be specified as binding a target for the sandwich (hopefully a slice of bread), but not a theme (which will vary as different items are placed on the target slice). When *make sandwich* is selected, the schema's target will be bound to the target of the first relevant action (e.g., the slice of bread to which the mustard is applied, assuming mustard is the first thing put on the bread). Subsequent actions within the scope of the *make sandwich* schema will use the same target – so the meat and the second slice of bread will be placed on the same slice of bread used for the mustard – until *make sandwich* is deselected and the target functional role is unbound.

When a representation of an object is unbound from a functional role the representation's node is inhibited, mirroring the inhibition of schema nodes upon deselection. As in the schema network, this inhibition continues until the activation of the deselected object representation is exceeded by that of a competitor.

3.4 Monitoring and error correction

The use of pre-conditions and post-conditions to modulate the top-down flow of activation within the schema hierarchy opens up the possibility of augmenting the basic contention scheduling system with mechanisms for monitoring and error correction. A high-level schema (such as filling and sealing a thermos) will have a post-condition and a set of component schemas. Each component schema will likewise have a post-condition. Under "correct" functioning the post-condition of a higher level schema should be satisfied when all component schemas are completed (or their post-conditions are otherwise satisfied). The extended model therefore also includes a monitoring mechanism that tests a schema's post-condition whenever a schema is deselected. If the post-condition is not satisfied, an error correction mechanism is invoked. In general, error correction may involve complex reasoning or problem solving and within the general supervisory system/contention scheduling framework the net effect of these processes would be to selectively excite or inhibit appropriate nodes within the schema network. Such complex and potentially open-ended processes have not been implemented. Rather, the simulations reported here adopt a greatly simplified approach to error correction, namely reactivating the failed schema. This simplified approach has proved to be highly effective in the restricted domains discussed below.

Monitoring and error correction may be considered as rudimentary supervisory processes. Under ideal conditions and as described below the basic model is able to simulate error-free behaviour in tasks of moderate complexity without calling upon these processes. They are only required to get behaviour back on track following error. They are therefore important for simulating extended sequences of errorful behaviour, such as that of frontal patients performing complex activities of daily living, because while such patients may make numerous errors, they nevertheless appear to continue "on task" following those errors.

3.5 On the relation between the current model and that of Cooper & Shallice (2000)

There are five main differences between the model reported here and that presented by Cooper & Shallice (2000). Three of these – the use of pre-conditions and post-conditions to gate the top-down flow of excitation within the schema network, the binding of objects within higher-level schemas, and the use of monitoring/error correction – have clear theoretical motivations and implications. The remaining two – the definition and subsequent normalisation of competition – are more implementational in nature. They are motivated by computational demands imposed upon the propagation of activation by the additional complexity of tasks such as the lunch packing task, and are not discussed further. Appendix C contains a detailed, assumption-by-assumption, list of differences between the models.

The rationales for object binding and monitoring/error correction have already been discussed, but the use of pre-conditions and post-conditions warrants further discussion. Within the earlier version of the model a schema's specification included a partially ordered set of subgoals necessary for successful completion of the schema. When a high level schema was selected, activation was passed to all component schemas that could achieve relevant subgoals. Execution of a schema was assumed to require successful completion of one component schema for each of the selected schema's subgoals. This is satisfactory only in the simplest of domains, when successful completion of all subgoals is necessary and sufficient for successful completion of a schema and when subgoals cannot fail. The requirements of more complex ADL suggest that this treatment of goals is a considerable simplification. The current model therefore extends subgoals to incorporate pre-conditions and post-conditions. Pre-conditions ensure that top-down excitation is not normally passed to a component schema until it is potentially relevant. Post-conditions provide additional flexibility in determining which subgoals of a selected schema are essential to the schema's successful completion. Together, these mechanisms yield a system with considerable flexibility in behaviour. For example, component schemas may be effectively concatenated, such that actions that conceptually belong at the end of one schema (e.g., discarding a spoon after it has been used to add sugar to a beverage) may be omitted when they are not required for the successful completion of a subsequent schema (e.g., stirring the beverage). Thus, at a theoretical level, the use of pre-conditions and post-conditions allows schemas, as abstractions, to apply in a wide range of situations. The earlier model would require separate schemas, for example, when preparing coffee with a sealed coffee jar and with an open coffee jar (differing only in the component schema for opening the coffee jar), or for stirring coffee when already holding a teaspoon and when not holding a teaspoon. Within the current model each case requires a single schema.

3.6 An instantiation of the model: The lunch packing task

In order to evaluate the extended model it is necessary to consider its instantiation in a specific task. The task considered here, preparing and packing a lunchbox, is one for which considerable empirical data (from normals and neurological patients) is available (cf. Schwartz, *et al.*, 1998, 1999; Buxbaum, *et al.*, 1998). The lunch packing task has six subtasks: wrap a snack, prepare and then wrap a sandwich, fill and then seal a thermos, and finally pack the prepared items into the lunchbox. Each subtask has a number of steps, many of which may themselves be further decomposed (e.g., applying mustard to the bread while making the sandwich involves picking up and opening a mustard jar). Control subjects perform the six subtasks in a variety of orders and with some interleaving of preparation and pack operations. They also make sporadic action slips such as attempting to screw the juice jar lid onto the mustard jar.

An appropriate schema hierarchy was developed for the complete task based on a standardised decomposition of each subtask. A fragment off the hierarchy is shown in Figure 3, and a complete listing of schemas is given in Appendix A. The schema hierarchy was complemented with an object representation network comprising nodes for the fifteen objects used by Schwartz, Buxbaum and colleagues in their “with distractor items” condition. Each object was represented by a set of features relating to, for example, size and shape. (See Appendix B for a complete list of objects and their features.) These features determined both how the objects behaved when they were acted upon, and the extent to which objects triggered (and were triggered by) schemas.

INSERT FIGURE 3 HERE

3.7 Model behaviour in the lunch packing task

The model’s behaviour is strongly dependent on the relative flow of activation within and between the various interactive activation networks. Four parameters control activation flow within the schema network: S_S (degree of self influence), L_S (degree of lateral influence), I_S (degree of intrinsic, or schema-to-schema, influence), and E_S (degree of extrinsic, or object-to-schema, influence). Similar parameters control activation flow within and between the other networks, with the subscript S, O and R used to indicate schema, object representation, and resource network parameters respectively. In addition, the impact of activation on any node within each network is subject to normally distributed random noise. The standard deviation of the noise distribution is given by the noise parameter, N. A further parameter, P, controls the degree to which activation of nodes persists from cycle to cycle in the absence of other influences. (See McClelland (1992) for further details of self, lateral, and noise parameters in interacting activation networks. See Cooper & Shallice (2000) and Cooper *et al.* (1995) for details of how individual parameters impact upon activation flow within the interactive activation action selection model, and Cooper & Shallice (1997) for discussion of the stability of the original model with respect to the various parameters.)

A number of simulations were performed at various points in parameter space in order to determine appropriate values for the simulation of well-structured behaviour. When $S_S = 0.23$, $L_S = 0.46$, $I_S = 0.50$, $E_S = 0.10$, $P = 0.87$ and $0.00 < N \leq 0.01$, the model is able to perform the complete task (approximately 60 actions) without error. Figure 4 shows a segment of well-formed behaviour from this region of parameter space. Departing from this region of the parameter space (e.g., increasing noise to 0.02 or greater) results in occasional errors similar in frequency and character to those of control participants. Figure 5 shows a segment containing one such error (an object substitution error, occurring with N = 0.04). Here, the model performed normally for most of the task, but then incorrectly packed the wrapped snack into the lunch box lid, instead of the lunch box. Subsequent items were correctly packed.[4] The error occurred because noise affecting object representations led to the lunch box lid being active as a target during the initial packing operation.

INSERT FIGURE 4 HERE

INSERT FIGURE 5 HERE

Action scripts generated by the model (such as those in Figures 4 and 5) were scored by a separate program which automated the scoring procedure developed by Schwartz, Buxbaum and colleagues for scoring patient behaviour on the lunch packing task. The procedure differentiates between the types of error shown in Table 1, and produces a standardised error score for each type of error and an accomplishment score for the entire task.

Once reasonable "default" parameter values had been determined, large regions of the parameter space were scanned in order to determine the sensitivity of the model to the values of the various parameters. In this, and all parameter studies reported here, the Express software (Yule & Cooper, 2001, 2003) was used for the co-ordination of simulations across a set of networked machines and for the collation and preliminary analysis of simulation results.

Figure 6 (left) shows the error surface obtained by averaging total errors produced over 20 trials for each parameter value, with S and L fixed (at 0.23 and 0.46 respectively) and with I_S and E_S varying between zero and one. The number of errors is indicated by the greyscale, with white corresponding to zero errors. There is a substantial region of roughly triangular shape on the left of the graph in which few errors occur (with I_S ranging from 0.35 to 0.80 and E_S ranging from 0.05 to 0.25), indicating that in the stable region the model is robust to changes in these parameters. Figure 6 (right) shows accomplishment scores for the same region of parameter space. High accomplishment scores are shown by lighter shades of grey. The error-free region is clearly also a region of high accomplishment (i.e., where the task is generally successfully completed), but as in both control data and patient data, high accomplishment scores do not correlate perfectly with low error scores – accomplishment scores may be very low despite moderate error production, in cases where the errors are mostly of the omission type, and commission errors of all types may contribute to an error score without compromising the accomplishment score.

INSERT FIGURE 6 HERE

Figure 7 (left) shows a second error surface, obtained by fixing I_S and E_S (at 0.50 and 0.10 respectively) and varying S and L (simultaneously within all networks) from 0.00 to 1.00. Corresponding accomplishment scores are shown in Figure 7 (right). Again, there is a substantial area in which few errors occur. Although the self influence parameter is quite highly constrained, the figure indicates that (at least in this region of the parameter space) the model is robust to changes in the lateral influence parameter.

INSERT FIGURE 7 HERE

4 Lesion Studies

Having established the basic stability of the model, a number of lesioning studies were performed to investigate theories of action disorganisation. These studies, which were all motivated by contemporary theories of action disorganisation or frontal dysfunction, involved varying some

[4]The lunchbox lid was not bound as a target for all packing operations because other objects were used as targets between the initial (erroneous) packing action and the later packing actions.

parameter from its default value and exploring the resultant behaviour of the model in light of the key empirical findings on action disorganisation isolated above. This section reports three studies in detail: varying the balance between top-down excitation of schemas and bottom-up, environmental, triggering of schemas, increasing noise in the schema network, and increasing noise in the object representation network. Several other studies motivated by contemporary theories of frontal dysfunction were also conducted (e.g., both persistence and self influence were decreased in an attempt to simulate goal decay (Duncan, 1995; Duncan *et al.*, 1995), lateral inhibition was decreased in an attempt to simulate a general inhibitory deficit (Verfaellie & Heilman, 1987; Fuster, 1997), and top-down excitation within the schema network was reduced in the absence of a corresponding increase in bottom-up excitation in an attempt to explore whether deficient top-down excitation alone could account for action disorganisation), but none of these studies yielded appreciable levels of commission errors, and so they are not described in detail.

Each study involved attempting to relate model behaviour to the behaviour of patients as one parameter was varied, with the degree of parameter variation mapping to patient severity. Several analyses are presented below for each study. First, unbiased sampling of behaviour from the full parameter range is presented and a two-way analysis of variance is used in order to determine the main effects of severity and distractor object presence and any interactions between these independent variables on each of the principal dependent variables. While statistically important, such effects are not necessarily reflected in the group data from patient studies because the group may not represent an unbiased sample from the assumed severity continuum. Thus, in Schwartz *et al.*'s (1998) study, there were many patients of mild to moderate severity and few patients of high severity. In fact, consideration of the raw error scores of Schwartz *et al.*'s (1998) patient group suggests severity was distributed according to Zipf's Law (Zipf, 1949). That is, if s is an index of severity, then $f(s)$, the frequency of patients of severity s, is given by

$$f(s) = k \, . \, s^{-\alpha}$$

where k is a constant of proportionality and α is approximately 1. This is also suggested by the distribution of standardised error scores shown in Figure 1 (which is roughly hyperbolic, as would be expected with a Zipf distribution), and is plausible given that the patient group was based on consecutive inpatient admissions: one would expect that beyond a certain baseline level necessary for admission as an inpatient, mild brain injuries would be more common than severe injuries.

Using the total error score as the index of severity, the log-log scatter plot of s against $f(s)$ for Schwartz *et al.*'s (1998) patients showed a strong linear trend, as would be expected from Zipf's Law, and regression analysis yielded a best fit with $\alpha = 1.089$ (accounting for 0.747 of the variance in the frequency distribution). Given this, in a second analysis for each study the model data were sampled according to a Zipf distribution with $\alpha = 1.089$ and converted to standardised error scores following the procedure of Schwartz *et al*. (1998).

The sampling procedure was as follows: The levels of damage within the model were ordered according to severity (e.g., in the case of increasing noise in the schema network, from least noise to most noise). Minimum and maximum levels of damage were then determined by selecting values of the parameter that gave a reasonable fit to the total error scores of the least and most severe patients. Cases equivalent to single patients with varying degrees of deficit were then selected from the severity distribution with the probability of selecting a case with damage d units from the minimum being proportional to $d^{-\alpha}$. 30 cases were selected in this way from the subset of simulation runs performed with distractors present. 30 additional simulation cases were then selected from the subset of simulation runs performed with distractors absent. These additional cases were matched pair-wise for level of damage with the first 30 cases. The standardised error scores for each pair where then averaged to produce a distribution of 30 simulated participants with dependent measures directly comparable to those shown in Figure 1.

In two of the three studies, where the distribution of standardised error scores appears promising, a third analysis is presented in order to drive empirical predictions. The analysis of variance results from the unbiased sample are not comparable with patient data for two reasons. First, they are based on an even sampling of all levels of damage. Second, they employ level of damage as a factor. As noted above Schwartz *et al.*'s (1998) group of CHI patients were distributed by severity according to Zipf's law, and there is every reason to expect that *any* clinical sample will be distributed in this way. It is also not possible to determine level of damage within any single patient in a general, non-task-specific, way. In the third analysis, the simulation data were therefore resampled and analysed using single-factor tests (i.e., t-tests) in order to determiner the model's predictions with respect to a clinical sample. Again, sampling assumed a Zipf distribution with $\alpha = 1.089$. This analysis used the largest possible sample from the simulation data. Thus, if 100 trials were initially performed at each level of the parameter, then all 100 trials in each condition were selected from the baseline value of the parameter, 47 (i.e., $100 / 2^{\alpha}$) trials were selected from the next value, 30 (i.e., $100 / 3^{\alpha}$) trials were selected from the next value, and so on. The size of the resulting sample, which we refer to as a "clinical" sample, depends on the number of levels of the parameter sampled within the range.

4.1 Study 1: Altering the Top-Down / Bottom-Up Balance within the Schema Network

As discussed in the introduction, it has been suggested that action disorganisation following brain injury is a result of reduced top-down excitation within a hierarchically organised action control system, resulting in increased sensitivity to the contingencies afforded by the environment for action. This proposal follows from Luria's (1966) claim that "frontal apraxia" (i.e., action disorganisation) is an extreme form of an executive disorder resulting from frontal lobe damage, and Shallice's (1982, 1988) account of frontal lobe executive disorder in terms of a loosening of SAS control over CS (cf. Schwartz *et al*., 1991). Cooper & Shallice (2000) provided computational support for this view by demonstrating that a model of simple ADL based on CS principles did show many qualitative features of action disorganisation when the balance of excitation to schema nodes was shifted away from top-down sources and towards bottom-up (i.e., environmental) sources. In order to further evaluate the hypothesis that action disorganisation is a consequence of reduced top-down excitation coupled with increased bottom-up excitation within a hierarchically structured action selection system we explored the effect of reducing I_S, the parameter governing the flow of top-down activation within the schema network, while increasing E_S, the parameter governing the flow of bottom-up activation on the schema network, on the behaviour of the revised model when performing the complex ADL of preparing and packing a lunchbox.

4.1.1 Method

The parameters *S*, *L* and *N* were fixed at their default values (0.23, 0.46 and 0.01 respectively). The model was run 100 times with distractor objects present and 100 times with distractor objects absent for values of I_S, the parameter specifying the degree of top-down excitation passed from selected schemas to their component schemas within the schema networks, ranging from 0.50 to 0.40 at intervals of 0.005 and E_S, the parameter specifying the degree of bottom-up excitation passed from the representation of objects, ranging from 0.10 to 0.20 at intervals of 0.005 (i.e., a total of $100 \times 2 \times 21 = 4200$ simulation runs). $I_S + E_S$ was held constant at 0.60 throughout all simulations.[5]

4.1.2 Results

The action scripts generated by each run of the model were scored using the automated scoring program described above. There was a strong and highly significant negative correlation between accomplishment score and the number of omission errors ($r = -0.992$, $d.f. = 4198$, $p < 0.001$). While

[5]The simultaneous variation of I_S and E_S was motivated by the need to provide a reasonable net level of excitation to the schema network. If E_S is fixed while I_S is decreased, corresponding to a decrease in top-down control with fixed bottom-up excitation, then there comes a point when there is insufficient excitation in the schema network to activate any schemas. The model then ceases to execute any actions and omission errors are recorded. Increasing I_S while E_S is decreased ensures action continues and provides scope for the generation of commission errors.

only 5% of errors were commission errors, the correlation between accomplishment score and the total number of errors of commission was also significantly negative ($r = -0.456$, $d.f. = 4198$, $p < 0.001$).

Figure 8 shows the mean number of errors for each parameter value, broken into addition, sequence, omission, and substitution errors. The fit with empirical data is poor. There is a clear lack of errors of commission, which were virtually at floor in both conditions. In fact, no substitution errors were observed in either condition, and while 14,867 omission errors were observed, there were only 140 sequence errors. The only other errors of commission were all action additions, with 659 such errors distributed evenly between the two experimental conditions. Statistical analysis confirmed that the manipulation of the level of I_s / E_S had a significant effect on total errors ($F(20, 4158) = 678.032$; $p < 0.001$), the number of omission errors ($F(20, 4158) = 680.790$; $p < 0.001$), and the number of commission errors ($F(20, 4158) = 57.864$; $p < 0.001$). There were also significant effects of distractor condition on total errors ($F(1, 4158) = 30.862$; $p < 0.001$), number of omission errors ($F(1, 4158) = 36.936$; $p < 0.001$) and number of commission errors ($F(1, 4158) = 19.912$; $p < 0.001$), but in each case the presence of distractors led to fewer errors of each type, rather than more errors. Finally, there was no interaction between level of I_S / E_S and distractor condition on total errors ($F(20, 4158) = 1.202$; *n.s.*), number of omission errors ($F(20, 4158) = 1.350$, *n.s.*) or number of commission errors ($F(20, 4158) = 1.388$; *n.s.*).

INSERT FIGURE 8 HERE

A subset of 60 simulation runs (corresponding to 30 simulated participants in each condition) was then selected from the entire set to form a biased sample using the Zipf distribution as described above. The most plausible fit to the patient data was obtained with I_S ranging from 0.450 (least severe) to 0.420 (most severe). Figure 9 shows the bar chart of standardised error scores for these 30 simulated participants.

INSERT FIGURE 9 HERE

Comparison of Figure 9 with Figure 1 supports the initial analyses: the behaviour of the model under this parameter manipulation is not comparable to that of Schwartz et al.'s (1998) CHI patients, even when realistic sampling biases are invoked. The manipulation predicts that most patients will produce only omission errors, something which is not true of Schwartz *et al.*'s (1998) CHI patient group.

4.1.3 Discussion

The simulation results suggest that action disorganisation cannot be accounted for in terms of an imbalance between top-down and bottom-up excitation within the schema network. While such an imbalance reproduces significant correlations between accomplishment and omission/commission error rates, it fails to account for the relative frequency of commission errors observed by Schwartz *et al.* (1998). It also fails to yield the correct main effects of distractor condition (i.e., more omission and substitution errors when distractors are present). In addition, it fails to predict a graded effect of severity: omission errors dominate behaviour when I_S falls to below 0.450, but greater reductions in I_S do not lead to more omission errors, or indeed to poorer accomplishment scores.

This negative result is at odds with the simulation results derived from the earlier version of the model, which demonstrated that a reduction in top-down excitation coupled with an increase in bottom-up excitation did provide a qualitative account of action disorganisation syndrome in the simpler task of coffee preparation. Addition and sequence errors were common in those simulations. The relative absence of such errors in the current simulations is due to two factors. First, sequence errors are discouraged by the use of strict pre-conditions and post-conditions introduced in order to simulate behaviour on the more complex ADL task of preparing and packing a lunchbox. Second, close examination of the model behaviour reveals that simple action additions are in fact common when I_S is below 0.450, but the scoring system is conservative and does not count these additions. Almost all of these additions take the form of repetitive toying behaviours (e.g., perseveratively picking up and then putting down an object). These behaviours were not scored by Schwartz *et al.* (1998). Hence they have also not been scored in the present work. They do, however, suggest an alternative interpretation of the parameter manipulation: that such a manipulation may provide an account of utilisation behaviour of the type described by Shallice *et al.* (1989; See also Schwartz *et al.*, 1991). One possible objection to this interpretation is the high rate of omission errors that occur when I_S is below 0.450. Previous descriptions of utilisation behaviour have not noted high rates of such errors. This may be because such studies have focussed on the behaviour as induced (Lhermitte, 1983) or incidental to a primary task (Shallice *et al.*, 1989), rather than on primary, naturalistic, task behaviour itself. Certainly previous studies have not examined utilisation behaviour within the context of a task as complex as that considered here. It is plausible that within such relatively complex tasks omission errors may arise from the complete failure to perform subtasks – a possibility not available within tasks traditionally used to investigate utilisation behaviour. The above interpretation, and the possible relation between utilisation behaviour and action disorganisation syndrome, is addressed in more detail in the general discussion.

4.2 Study 2: Increasing Noise within the Schema Network

Deficits in action selection following frontal injury occur in a wide range of patients. The deficit appears to be the result of generalised rather than localised damage, and its severity varies along a continuum (arguably with normals at one extreme: cf. Schwartz *et al.*, 1998). These factors suggest that the deficit might be due to a non-specific disruption to the precision of the action selection system(s). Such damage may be simulated within the current model by increasing N_S, the noise in activation flow throughout the schema network. Increasing schema noise degrades the effectiveness of selective excitation and inhibition within the schema network. Thus, and in order to investigate the hypothesis that action disorganisation is a consequence of generalised damage within the schema network, we compared the effects of increasing N_S on model behaviour in the two experimental conditions (i.e., with distractor objects absent and present).

4.2.1 Method

The parameters S, L, I_S and E_S were fixed at their default values (0.23, 0.46, 0.50 and 0.10, respectively). The model was run 100 times with distractor objects present and 100 times with distractor objects absent for values of N_S, the parameter specifying the standard deviation of noise within the schema network, ranging from 0.01 to 0.25 at intervals of 0.01 (i.e., a total of $100 \times 2 \times 25 = 5000$ runs).

4.2.2 Results

The action scripts generated by each run of the model were scored using the scoring program described above. As in Study 1, there was a strong and highly significant negative correlation between accomplishment score and number of omission errors ($r = -0.975$, $d.f. = 4998$, $p < 0.001$). The correlation between accomplishment score and number of commission errors was more mild ($r = -0.429$, $d.f. = 4998$, $p < 0.001$), but still negative and highly significant, as in Schwartz *et al.*'s (1998) CHI patient data.

Figure 10 shows the mean standardised error rates for each value of N_S (with N_S decreasing from left to right), broken into the four standard categories. It is apparent that with increasing levels of noise, both omission and commission errors increase. Inspection of the data suggest some clear differences between experimental conditions, with signs of increased rates of omission errors and substitution errors when distractor objects are present. This is supported by statistical analysis. There was an effect of level of N_S on total errors ($F(24, 4950) = 299.043$; $p < 0.001$), on the number of omission errors ($F(24, 4950) = 106.609$; $p < 0.001$), and on the number of commission errors ($F(24, 4950) = 432.811$; $p < 0.001$). There was also an effect of distractor condition on total errors ($F(1, 4950) = 68.114$; $p < 0.001$), number of omission errors ($F(1, 4950) = 53.508$; $p < 0.001$) and number of commission errors ($F(1, 4950) = 14.589$; $p < 0.001$). There was a mild interaction between level of N_S and distractor condition on total errors ($F(24, 4950) = 1.583$; $p < 0.05$), but not on number of omission errors ($F(24, 4950) = 1.270$; *n.s.*) or on number of commission errors ($F(24, 4950) = 0.586$; *n.s.*). The interaction appears to be the result of a decreased effect of N_S and condition on errors at the extremes of the N_S range.

INSERT FIGURE 10 HERE

Figure 11 shows the corresponding bar chart of standardised error scores for 30 simulated participants sampled according to the Zipf distribution as described above. Comparison of Figure 11 with Figure 1 suggests that this manipulation is worthy of further consideration. Omission errors are, as ever, common, but other types of error occur at non-negligible rates, and the proportion of commission errors appears to be substantially greater for low error producers than for high error producers.

INSERT FIGURE 11 HERE

A "clinical" sample consisting of 564 trials was constructed based on a Zipf distribution according to the procedure described above. Between-condition *t*-tests on standardised scores for the various error types with this sample revealed that the presence of distractor objects led to significant increases in omission errors (increasing from 15.66 to 19.88 omissions per 100 opportunities: $t(562) = 2.302$, $p < 0.05$) and object substitution errors (increasing from 0.14 to 1.06 object substitutions per 100 opportunities: $t(562) = 7.339$, $p < 0.001$), but not sequence errors ($t(562) = -0.799$, *n.s.*) or action additions ($t(562) = -1.697$, *n.s.*). Ignoring the 323 trials from the clinical sample with zero errors and separating the remaining 241 trials into two groups based on total error score (ignoring distractor condition) led to standardised commission proportions of 0.3721 for the low error producers and 0.0290 for the high error producers. The difference between groups was highly significant ($t(239) = 12.192$, $p < 0.001$).

4.2.3 Discussion

Increasing noise within the schema network appears to capture many of the principal characteristics of action disorganisation. The dominant error type in both experimental conditions is that of omission. Additions, substitutions, and sequence errors occur, but at substantially lower levels. While these levels are lower than those observed in the patient data, the negative correlation between accomplishment and number of errors of commission, reported by Schwartz *et al.* (1998) for CHI patients, is present. The correlation observed in the model data is weaker than that observed in the patient data, but the effect of schema noise on commission errors is significant: it remains the case that failure to accomplish the task is not entirely due to errors of omission. At the same time, low error producers produce a greater proportion of commission errors (as in the patient sample).

The manipulation of noise within the schema network also captures several between-condition effects: for higher values of noise, both omission and substitution errors are more frequent when distractor objects are present than when they are absent. The effects of distractor objects on action additions and sequence errors is small, and the effect of distractor objects is greater (in absolute terms) on omission errors than on substitution errors.

These simulations, and in particular the similarities between Figure 1 and Figure 11, support the view that action disorganisation results from a generalised deficit within a hierarchical schema network, a deficit that may be modelled in terms of increased noise within that network. The fit with patient data is not perfect, but the key findings – the occurrence of errors of commission in both conditions and the significant increase in omission and object substitution errors when distractor objects are present – are in marked contrast to the findings of Study 1.

A sceptic might argue that the pattern of errors both observed in the patients and obtained in this simulation is not surprising. Multiple factors may impact upon the selection of any individual action and the objects to which it is applied. Consequently errors of action are likely to be determined by multiple interactions (Reason, 1990). Furthermore, different forms of breakdown within the action control system might yield qualitatively similar errors profiles (Buxbaum, *et al*, 1998). Alternatively, any qualitative variation between Schwartz *et al.*'s (1998) patients may have been obscured by the group study methodology employed. If such factors do yield a blurred picture of action disorganisation, then, the sceptic may argue, it is not surprising that increased noise, a blunt tool at the best of times, should match this picture. Perhaps the most telling counters to this argument are the facts that 1) even when one controls for opportunities, errors of the various types are not equally frequent (as an atheoretic analysis of noise might suggest), and 2) severity and condition interact in their effects upon omission and substitution errors, but not in their effects upon addition and sequence errors, both in the patient data and in the simulation results. Thus, the model predicts differential effects of schema noise, and these differential effects are precisely those seen in the patient data.

4.3 Study 3: Increasing Noise within the Object Representation Networks

Several factors suggest that further investigation of the effects of noise is warranted. Reciprocal interactions between the schema and object representation networks within the model mean that noise in either network will immediately propagate to the other networks. Given that noise is, as noted above, a blunt tool, it is conceivable that noise affecting the object representation networks will yield similar behavioural effects to noise affecting the schema network. If the effects of schema noise and object representation noise are indistinguishable, then the interpretation of action disorganisation syndrome as a disturbance of schema activation will require further consideration. Thus, it is of considerable interest to determine whether the effects of noise in the schema network may be distinguished from the effects of noise elsewhere in the system. For these reasons an additional study was conducted in which N_O, noise in the object representation networks, was varied.

4.3.1 Method

Study 2 was repeated with N_S fixed at its default value (0.01) and variable levels of N_O. That is, the parameters S, L, I_S and E_S were fixed at their default values (0.23, 0.46, 0.50 and 0.10, respectively) and the model was run 100 times with distractor objects present and 100 times with distractor objects absent for values of N_O, the parameter specifying the standard deviation of noise within the object representation networks, ranging from 0.01 to 0.25 at intervals of 0.01 (i.e., a total of $100 \times 2 \times 25 = 5000$ runs).

4.3.2 Results

The action scripts generated by each run of the model were scored using the scoring program described above. As in studies 1 and 2, there was a strong and highly significant negative correlation between accomplishment score and number of omission errors ($r = -0.974$, *d.f.* = 4998, $p < 0.001$). The correlation between accomplishment score and number of commission errors was, however, mildly positive ($r = +0.172$).

Figure 12 shows the mean standardised error rates for each value of N_O (with N_O decreasing from left to right), broken into the four standard categories. A pattern similar to Figure 10 is present, though substitution errors appear to be more frequent and action additions less frequent. As in Study 2, inspection of the data suggest some clear differences between experimental conditions, with increased rates of omission errors, substitution errors and action additions when distractor objects are present. This is supported by statistical analysis. There was an effect of level of N_O on total errors ($F(24, 4950) = 212.511$; $p < 0.001$), on the number of omission errors ($F(24, 4950) = 110.033$; $p < 0.001$), and on the number of commission errors ($F(24, 4950) = 39.036$; $p < 0.001$). There was also an effect of distractor condition on total errors ($F(1, 4950) = 49.031$; $p < 0.001$), number of omission errors ($F(1, 4950) = 20.483$; $p < 0.001$) and number of commission errors ($F(1, 4950) = 13.909$; $p < 0.001$). There was no interaction between level of N_O and distractor condition on total errors ($F(24, 4950) = 1.366$; *n.s.*), number of omission errors ($F(24, 4950) = 0.982$; *n.s.*), or number of commission errors ($F(24, 4950) = 0.316$; *n.s.*).

INSERT FIGURE 12 HERE

Figure 13 shows a bar chart of standardised error scores for 30 simulated participants sampled according to the Zipf distribution as described above. Comparison of Figure 13 with Figure 1 and

Figure 11 suggests that this manipulation, like that of Study 2, is worthy of further consideration. Once again omission errors are common, but other types of error occur at non-negligible rates, and as in Study 2 the proportion of commission errors appears to be substantially greater for low error producers than for high error producers.

INSERT FIGURE 13 HERE

A "clinical" sample of the simulated data was constructed as for Study 2, and between-condition *t*-tests on standardised scores for the various error types were performed. The sample consisted of 604 trials, 310 of which were error free. The *t*-tests revealed a significant effect of distractor presence on omission errors (increasing from 9.58 to 13.33 omissions per 100 opportunities: $t(602) = 2.763$, $p < 0.005$), but not on other error types. Separating the errorful sub-sample into two groups based on total error score (ignoring distractor condition) led to standardised commission proportions of 0.7966 for the low error producers and 0.1220 for the high error producers. The between-group difference was highly significant ($t(292) = 30.385$, $p < 0.001$). This sampling procedure also reversed the sign of the correlation between accomplishment and commission errors, suggesting that the correlation is non-linear.

4.3.3 Discussion

Noise in the object representation networks appears to yield behaviour that is similar both to that produced by noise in the schema network and to that of the various patient groups. It provides a good account of the relative proportions of commission and omission errors as a function of severity – yielding quantitatively appropriate values for standardised commission proportions in both low and high error producers – and of the effect of distractor presence on the various error types. It also leads to a distribution of error types that is plausible (i.e., not completely dominated by omission errors). In fact, the only questionable aspect of the model's behaviour under this manipulation is the positive correlation between accomplishment and commission errors, but even this effect was reversed when clinical biases in sampling were taken into account. Noise in the object representation networks therefore appears to provide a viable alternative to noise in the schema network as an account of action disorganisation syndrome.

The similarities between behaviour produced by increasing noise in the schema and object representation networks should not be surprising. As suggested above, reciprocal interactions between schema nodes and object representation nodes are likely to mean that any noise in one network is quickly propagated to other networks. However, the effect of noise in the object representation network is not merely to add noise to schema activations. The transmission of noise to the schema network from the object representation networks is modulated by schema triggering functions. Thus, noise in the object representation networks has the effect of degrading triggering excitation of schemas. It is for this reason that noise in the object representation does not merely result in increased levels of object substitution errors: such noise affects the activation of schemas – and hence the schemas that are selected – as much as the selection of objects to fill argument roles once a schema has been selected.

Notwithstanding the general similarities in behaviour produced by this manipulation and that of Study 2, several clear differences are evident from comparison of Figure 10 and Figure 12. Noise in the schema network results in near linear increases in the rates of all error types with severity, with action additions being the most common commission error. Noise in the object representation networks yields lower rates of action additions (and sequence errors), but higher rates of object substitution errors. The linear increase in error rates is also only evident for mild increases in the parameter. These differences, as discussed below, suggest that detailed empirical investigation may be able to discriminate between the two forms of disruption modelled by noise.

5 General Discussion

5.1 Model behaviour and its implications for theories of action disorganisation syndrome

The three simulation studies demonstrate that the disorganisation seen in the everyday behaviour of CHI patients cannot be accounted for purely in terms of an imbalance of top-down and bottom-up sources of activation within a hierarchically organised action selection system. Rather, they suggest that the disorganisation is better characterised in terms of disturbances either to activation propagation within the schema network or from the object representations triggering schemas. Such disturbances, modelled by increasing noise in the schema (Study 2) and object representation (Study 3) networks, can account for the majority of the behavioural phenomena outlined at the beginning of this paper. Before discussing some implications of this result for theories of action disorganisation, we consider some more general questions relating to the origins of error within the model.

5.1.1 On the origins of errors

It is clear from the simulation results that errors of each type produced by the model do not have a simple origin. If this were the case, one would expect each parameter manipulation to produce a characteristic type of error. This is not the behaviour observed in patients (i.e., there are not patients who make purely object substitution errors or purely sequence errors – instead, action disorganisation patients make a mix of errors) or in the model when a parameter is varied from its default value. It is therefore of interest to consider the origins of the various error types.

Sequence errors typically arise because a schema becomes active when its pre-condition is not satisfied. For example, a typical anticipation-omission error in the lunch packing task involves pouring from a sealed container. This error occurs when the pour schema becomes active even though its pre-condition (that an open container be held) is not satisfied. This may occur if, for example, there is too much noise in the schema network. Sequence errors can also arise if noise in the object representation networks leads to inappropriate or untimely triggering of a schema. Noise in all networks has a particular strong effect in the early stages of competition, when the activations of several schemas or object representations are relatively similar. Sequence errors are arguably less common in the simulation studies than in patient behaviour, but this is largely because pre-conditions act in an all-or-none fashion. Use of graded pre-conditions would result in increased rates of sequence errors.

One important type of sequence error – that of perseveration – can occur as a result of the error recovery mechanism. This mechanism works by attempting to repeat a schema when, on completion, the schema’s post-condition fails. If much of the schema completed successfully, this can result in a perseveration. Alternatively, perseverative errors may arise from the same kind of inappropriate activity in the schema network that results in other forms of sequence error.

Object substitution errors arise when an apparently appropriate schema is selected but an incorrect or inappropriate object representation is most active. Typically this is a result of a malfunction in the competitive processes within the object representation networks (e.g., because of noise in the object representation networks), but it may also reflect an error in schema selection (e.g., schemas for one subtask becoming active when objects for another subtask are already highly active).

There are several ways in which action additions may arise. First, they may simply be particularly flagrant object substitution errors that cannot obviously be interpreted within the ongoing task. Second, action additions may reflect selection of an inappropriate schema due to an error in the resolution of schema competition (e.g., due to noise in the schema network). Third, action additions may result from triggering of an inappropriate schema due to inappropriate activity in an object representation network. Only the last of these can truly be classified as utilisation behaviour, but the different possible origins of action additions cannot be distinguished without recourse to the state of the schema and object representation networks.

The final type of error produced by the model is that of omission. Such errors are common and generally result when the model wanders “off task” after making some other kind of error. Such wandering can result in failure to complete the task – a behaviour observed by Schwartz *et al.* (1998) in their more severe patients. Omission errors may also arise if a schema is inappropriately deselected (e.g., because its activation is not sustained until all of its necessary sub-schemas are completed). Given the first of these origins of omission errors, it is likely that extensions to the model in the form of additional error correction procedures the keep the model going would reduce the number of omission errors, leading to relatively more commission errors. While omission errors are arguably too frequent in the behaviour of the lesioned model, such extensions have not been attempted for two reasons. First, whilst error monitoring is computationally simple, full error correction can require general problem solving. If in the lunch packing task, for example, the thermos is packed into the lunch box before being filled, then significant problem solving is required to plan appropriate corrective behaviour. Second and more pertinently, as is clear from Luria's analysis cited in the introduction, patients with severe frontal injuries appear to show limited monitoring and error correction. Implementation of complex error correction procedures would therefore seem inappropriate when modelling behavioural disorders such as action disorganisation syndrome.

It is certainly the case that a high rate of omission errors occurs in situations where at times the model has gone sufficiently off course that other types of (codable) error cannot occur. Similarly, the omission of entire subtasks may affect the opportunity for other types of error.[6] While this does reduce the sensitivity of the coding system somewhat, it is worth noting that the simulation correctly predicts increasing rates of all three other error types with increasing noise in the schema network: for the object network the rate of the other error types remains roughly constant with increasing noise.

5.1.2 On disorders of action selection

It appears that the key features of action disorganisation syndrome may be accounted for either by a generalised disturbance of schema activation or by a generalised disturbance to the triggering of schema activations from object representations (or both, as increased noise in both networks also leads to behaviour comparable to action disorganisation syndrome). The similarity in behaviours resulting from these two conceptually distinct forms of disturbance is ultimately due to the reciprocal coupling between schemas and object representations. The similarities mean, however, that the simulation results may be interpreted in at least two ways. First, action disorganisation syndrome in all patient groups studied by Schwartz, Buxbaum and colleagues might be the result of a single functional deficit (modelled by noise in either the schema network, the object representation networks, or indeed both). Second, and more intriguingly, the behaviourally similar deficits in action organisation exhibited by the various patient groups may be due to distinct functional impairments.

The first interpretation is consistent with Schwartz *et al.*'s (1998) resource hypothesis: that action disorganisation in CHI, LCVA and RCVA patients is the result of a single functional deficit characterisable in terms of a reduction in cognitive resources. Such a reduction in resources is likely to result in a generalised increase in confusability between similar representations within action-related subsystems (i.e., of schemas and of object representations), and hence can be modelled by increased noise within all networks.[7]

---

[6] In theory the patient data could also be affected in this way; however, the evidence suggests otherwise. In a re-analysis of the MLAT data, Schwartz (unpublished) identified all instances in which entire subtasks were omitted and corrected error and opportunity counts accordingly. Thus, the steps within omitted subtasks no longer contributed to the count of step omissions, and they were deemed to afford no opportunity for commission errors. This reanalysis did not alter the major findings. In particular, standardized error rates remained highest for step omissions, followed by sequence and substitution errors respectively; perseverations and reversals were rare; and error patterns were consistent across patient groups.

[7]The notion of cognitive resource as appealed to be Schwartz *et al.* (1998) should not be confused with the notion of a cognitive resource in the interactive activation model. In the former, a cognitive resource is something consumed by a process, so processing is in some way limited by available resources. In the latter, a cognitive resource is a subsystem (e.g., a language processing subsystem) that may be called upon in order to carry out a schema, so a resource may be allocated during execution of a schema.

While the simulation studies reported here cannot rule out the above (i.e., first) interpretation, the second interpretation is also worth pursuing as it is consistent with neurological evidence that suggests action disorganisation syndrome and ideational apraxia have distinct origins. In addition and as described below, it yields clear and testable predictions relating to subtle between-group differences in the errorful behaviour of the various patient groups. This second interpretation is also consistent with Buxbaum *et al.*'s (1998) suggestion that multiple sources of breakdown in human action selection may result in similar behavioural disturbances.

If we assume that disorganisation of action in different patient groups is a consequence of distinct functional impairments, then a plausible account of the simulation findings is that the action disorganisation of CHI patients is a consequence of a generalised disturbance to schema activation (as intentional control and the maintenance of task representations, generally regarded as frontal functions, are commonly disrupted in CHI), whereas the action disorganisation of patients with left temporoparietal damage (traditionally regarded as ideational apraxics) is a consequence of a disturbance to schema triggering from object representations.

The above interpretation accounts for the results of the group studies of Schwartz, Buxbaum and colleagues, but does not fully account for the behaviour of the two patients studied by Humphreys & Forde (1998: see also Forde & Humphreys, 2002). Recall that the behaviour of these patients differed from those studied by Schwartz, Buxbaum and colleagues in two respects. First, they produced high rates of perseverative errors and second the presence of distractor objects did not appear to affect their behaviour on the set of tasks studied. One potential reason for these differences lies in the relative severity of the patients studied by Humphreys & Forde (1998). The patients of Schwartz, Buxbaum and colleagues produced on average 1 to 2 errors per task, while those of Humphreys & Forde (1998) produced on average 6 to 7 errors per task. Indeed, the severity and behaviour of the Humphreys & Forde patients are more comparable to those of earlier patients described by Schwartz *et al*. (1991: HH, a severe stroke victim) and Schwartz *et al*. (1995: JK, a severe CHI patient), both of whom produced significant numbers of perseverative errors on some tasks. The differences may mean that the behaviour of these more severe patients is affected by other factors beyond a non-specific disruption of activation within the schema network. Indeed, while the model does produce perseverative errors when noise is increased in the schema and/or object representation networks, they are more frequent when self influence is high and/or lateral inhibition is low. One possibility therefore is that these more severe patients also have an inhibitory deficit.

The results of Study 1 also bear further interpretation. The model exhibits a pure form of utilisation behaviour following decreased top-down and increased bottom-up activation within the schema network. This corresponds very closely to the account of utilisation behaviour offered by Lhermitte (1983) and Shallice *et al.* (1989), but effectively the same account has been given for action disorganisation syndrome (Schwartz *et al.*, 1991; Cooper & Shallice, 2000) and for ideational apraxia (Rumiati *et al*., 2001). Study 1 supports the former view – that utilisation behaviour results from decreased top-down and increased bottom-up activation within the schema network. Together with studies 2 and 3, it also suggests that utilisation behaviour is distinct from both action disorganisation syndrome and ideational apraxia, and that utilisation behaviour can in principle dissociate from these two other disorders of action.

5.1.3 Model predictions

The proposed interpretation of the three simulation studies presented here leads to several predictions. First, if utilisation behaviour and action disorganisation syndrome arise from distinct disorders, then the disorders should dissociate and should have distinct behavioural consequences on ADL. Thus, the interpretation predicts that some patients (presumably those with localised medial bilateral frontal damage) will exhibit pure utilisation behaviour with toying and omissions due to a tendency to move off-task, but with few genuine object substitution or sequence errors, while others (e.g., CHI patients and those with more wide-spread neural damage) will exhibit a more generalised action disorganisation including non-negligible rates of all error types.

Second, if action disorganisation syndrome is a consequence of generalised frontal damage leading to a disturbance to activation within the schema network while ideational apraxia is a consequence of temporoparietal damage affecting schema triggering by object representations, then there should be subtle but in principle measurable differences between the groups on ADL. First, action disorganisation syndrome patients should show a tendency towards more action addition errors, while IA patients should show a tendency towards more object substitution errors. Second, while both groups should be sensitive to the presence of distractor objects (and produce more omission errors in their presence), action disorganisation syndrome patients should also produce more object substitution errors when distractors are present, while IA patients should show uniformly high rates of object substitution errors. Should these predictions, which remain to be tested, fail to hold, the model itself will not be falsified, though the interpretation suggested here will be.

5.2 Difficulties in the study of action selection and its disorders

There are several major difficulties in assessing theories and models of the breakdown of complex sequential action selection. These difficulties revolve around the establishment of appropriate target empirical phenomena. In some domains (e.g., acquired dyslexia: cf. Hinton & Shallice, 1991; Plaut & Shallice, 1993), target phenomena may be derived from case studies of a number of individual patients by having each patient perform hundreds of trials using different types of stimulus and/or under different experimental conditions. The practicality of this approach is limited within the domain of complex sequential action selection because there are a limited number of tasks that might be investigated, individual tasks are relatively time-consuming (taking tens of minutes, rather than seconds, to complete), and objective means of controlling task difficulty are not available. In addition, having one patient perform the same task multiple times in order to determine the stability of a deficit is likely to introduce practice effects. In order to work around this we have used group data derived from participant performance on a range of tasks, with between-task differences in the number of opportunities of each type of error being controlled for by working with standardised error rates.

Neither of the above workarounds is entirely satisfactory. Data from patients with unusual patterns of deficit can be mistaken for noise within group studies. Thus, while Schwartz *et al.* (1998) argue that the data shown in Figure 1 represents patients on a continuum with increasing rates of omission errors as severity increases, the data are equally compatible with different subgroups of action disorganisation syndrome, some of which involve primarily sequence errors (patients 15, 16, 21, 23 and 24 in Figure 1), object substitution errors (patient 14) or some combination of sequence and object substitution errors (patients 13 and 20). In fact, the variability of individual performance seen in the simulation results (cf. Figures 11 and 13) provides some support for Schwartz *et al.*'s claim of a single deficit underlying the disorganization of behaviour in their CHI patients. In order to be sure of this, however, it would be necessary to obtain additional data, particularly from less severe CHI patients, on a wider range of ADL tasks.

A further difficulty relates to scoring behaviour. In abstract terms, quantitative analysis requires the mapping of sequences of goal-directed actions onto one or more dependent measures. Humphreys and Forde (Humphreys & Forde, 1998; Humphreys *et al.*, 2000; Forde & Humphreys, 2002) have focussed on the different types of error as a reasonable measure, while standardised error scores (which control for opportunities for error) have been used here and in the more recent work of Schwartz Buxbaum and colleagues (Schwartz *et al.*, 1998, 1999; Buxbaum *et al.*, 1998; Giovannetti *et al.*, 2002) and earlier work by Schwartz *et al.* (1991, 1995) coded behaviour in terms of "crux" actions (the key action within a goal directed action sequence) and "independents" (actions within the scope of a crux which did not contribute to the achievement of the sequence's goal).

The difficulty is that coding of errors is not entirely objective. It is conceivable, for example, that an error such as adding ketchup to coffee results from pure utilisation of the ketchup (an action addition in the system of Schwartz *et al.* 1998) or from an object substitution in which ketchup and cream were confused. One reason for this difficulty is that it is frequently not possible to determine the true intentions that culminate in errorful behaviour. This is especially true with respect to the flagrant errors of more severe frontal patients – errors that may be difficult to interpret within the context of an ongoing task. Within the model it is tempting to use internal state information (i.e., information regarding which schemas are selected) to resolve such coding difficulties, but this is not helpful since such an approach cannot be applied to patient protocols.

Even if an objective method of classifying errors could be specified, different tasks provide different opportunities for error (Schwartz *et al.*, 1991; Forde & Humphreys, 2002), and so it is still necessary to control for between-task differences. While standardising error scores attempts to do this, such scores are subjective because the number of opportunities within a task for each type of error is itself subjective. It is difficult, for example, to quantify the number of opportunities for action additions within a task, and the standardisation process will be confounded as long as there exist certain errors that are ambiguous as to type.

5.3 Neural localisation

The case studies and group studies discussed in the introduction, together with the interpretation of action disorganisation syndrome, ideational apraxia and utilisation behaviour presented here, allow some comments to made with regard to neural localisation of some of the processes that make up the model. The basic action disorganisation syndrome as a consequence of extensive frontal lesions suggests that prefrontal cortex (PFC) is involved in regulating or modulating activation within the schema network, perhaps by ensuring that pre-conditions and post-conditions are appropriately applied or by maintaining schema activations throughout a task. Substantial PFC lesions reduce the effectiveness with which schema activation processes operate, resulting in confusions between competing schemas, and ultimately action disorganisation syndrome.

The assumption that ideational apraxia involves a disturbance to the triggering of schemas elicited by the representation of objects suggests that processes in the left parietal-temporal junction region are involved in such triggering. This derives from the traditional localisation of ideational apraxia (e.g., De Renzi & Lucchelli, 1998; Rumiati *et al.*, 2001). However, the findings of Schwartz *et al.* (1998) that RCVA patients show similar disorganisation of action above and beyond any effects of neglect suggests that the right temporoparietal structures may also play some role. On the perspective derived from De Renzi & Lucchelli the object representations in left temporoparietal regions would not be those classically associated with object recognition in the ventral stream. Instead they would be more likely to be ones in the dorsal stream, which doubly dissociate from those in the ventral stream (Rumiati et al., 2004). They might thus correspond to action-triggering structural descriptions used in a direct route to action (see Humphreys & Riddoch, 2003). This separation between action-triggering structural descriptions and object recognition systems in the ventral stream can explain why individual objects can be recognised correctly but then be used in error in the context of everyday action (e.g., patient HG: Forde & Humphreys, 2000; patient HB: Buxbaum *et al.*, 1997).

Utilisation behaviour, and in particular the claim that it results from bilateral medial frontal damage, suggests that medial frontal structures are involved in inhibiting object relevant behaviours in favour of intentional control. The suggestion is that both top-down (frontal) and bottom-up (temporoparietal) activations combine in the activation of schemas, but that medial frontal structures are involved in weighting the contributions of each, but that medial frontal structures are involved in potentiating the contributions of each (see, e.g., Stuss *et al.*, 1995). More specifically, the SMA is involved when no external cues are available to direct action (Godberg, 1985; Passingham, 1993). In other words, top-down activation which would be necessary in the model to overcome potential utilisation behaviour would involve structures on the medial surface of the frontal cortex which are typically damaged in utilisation behaviour patients (see, e.g., Boccardi *et al.*, 2002).

The actual resolution of competition between schemas may well be performed by the basal ganglia. There is accumulating evidence (cf. Redgrave *et al.*, 1999) that the basal ganglia implement a mechanism for the selection and allocation of resources to competing systems, and Gurney *et al.* (2001a, 2001b) provide a computational account of basal ganglia function within the domain of simple (non-sequential) action selection that is broadly consistent with the model presented here.

Finally, higher-level functions such as monitoring and error correction, which it is hypothesised may modulate activation within the schema network, are likely to be functions of PFC (Shallice & Burgess, 1996; Shallice, 2002). Action disorganisation syndrome appears to involve an impairment to these processes as well as to the lower-level processes involved in regulating schema activation.

5.4 Related models of action selection

While there are numerous theories of frontal function that may be recruited in an attempt to account for action disorganisation syndrome, there are few computational accounts of the disorder. One model of tangential relevance is that of Kimberg & Farah (1993), who provide "a unified account of cognitive impairments following frontal lobe damage" implemented within the ACT-R cognitive architecture (Anderson & Lebiere, 1998). The model explores the hypothesis that frontal lobe impairments arise from a weakening of associations between working memory representations, and while it accounts well for a range of such impairments, Kimberg & Farah (1993) do not discuss the model's predictions with respect to action selection within either simple or more complex ADL.

More relevant is the recurrent connectionist account of action selection developed by Botvinick & Plaut (2002, 2004). This model encodes action sequences in a non-hierarchical recurrent network, using feedback connections to allow the action at each time step to be determined by the current input (what is held and what is in view) and a representation of task context. Intriguingly, a standard learning algorithm (back-propagation through time: Williams & Zipser, 1995) is capable of learning a suitable representation of task context. The model has been shown to provide a plausible account of several of the basic effects of action disorganisation syndrome in simple ADL (e.g., preparing a cup of tea or coffee: Botvinick & Plaut, 2004), but it has not as yet been applied to more complex ADL, or to situations involving variable arrays of objects. The former raises difficulties related to scaling and catastrophic interference. Adequate performance on the tea and coffee tasks requires that the recurrent network be trained for at least 10,000 epochs, with all variants of each task interleaved within each epoch. If the network is to learn additional tasks, then significantly more training is likely to be required, and if all tasks are not interleaved during training then tasks presented and acquired early in training will be over-written by those presented later in training. The latter appears to require extending the model either with additional output actions (to fixate on additional objects) or with some additional mechanism to map between the existing output actions (e.g., fixating and subsequently acting on relevant objects) and actual behaviour (e.g., fixating and subsequently acting on a distractor object). The interaction of the model with higher cognitive processes such as monitoring and error correction also appears to be problematic because such higher processes appear to require a representation of goals and subtasks, yet the recurrent network model explicitly eschews such representations (cf. Cooper, 2002).

Yet another alternative is proposed by Humphreys & Forde (1998: see also Humphreys *et al.*, 2000), who suggest that the sequential organisation of action may be due to processes of "competitive queuing" (Houghton, 1990). The proposal, which has not been implemented, shares much with the current model in that action is the result of a selection mechanism operating on a set of action nodes, with lateral inhibition and self influence operating on those nodes. The key difference is that top-down excitation is hypothesised to apply an activation gradient to scheme/action nodes. The proposal is promising, particularly because Hebbian mechanisms can be invoked to account for one-trial learning, but there are technical difficulties in specifying how hierarchical action may be encoded. Existing applications of competitive queuing have not addressed this issue.

One area where the various models may be distinguished relates to disorders affecting the rate of behaviour. Previous work has applied an earlier version of the model presented here to disorders affecting the rate of action selection (specifically, amphetamine psychosis and bradykinesia: see Cooper & Shallice, 2000). Interactive activation, as in the current model and the proposal of Humphreys & Forde (1998), provides a natural substrate within which to account for disorders of rate, and it is unclear how such disorders may be accounted for within the recurrent network proposal of Botvinick & Plaut (2002, 2004). More generally, a substantial advantage of the current model over the above alternatives is that it provides an account of a range of disorders, including action disorganisation syndrome, ideational apraxia and utilisation behaviour, as well as disorders of rate. These disorders are largely accounted for by modifying distinct parameters within the model. Thus, while the multiplicity of parameters within the model may initially appear problematic, it is supported by the multiplicity of dissociable deficits in action selection.

5.5 Conclusion

We have generalised the Cooper & Shallice (2000) model of action selection in simple ADL to more complex ADL, and demonstrated that the model, when lesioned, captures several empirical effects of brain injury on the performance of everyday action. While the previous interpretation of action disorganisation syndrome as an imbalance of top-down and bottom-up activation within a hierarchically structured schema network was found to be inadequate, two other manipulations, increasing noise in the schema network and increasing noise in the object representation networks, were found to provide good accounts of the syndrome, particularly with regard to the effects of severity and distractor objects on behaviour within complex ADL. Additionally, interpretation of utilisation behaviour as an imbalance of top-down and bottom-up activation within the schema network, action disorganisation syndrome as a general disturbance of schema activation (modelled by noise in the schema network), and ideational apraxia as a general disturbance of schema triggering (modelling by noise in the object representation networks), lead to several predictions. While the action domain presents peculiar difficulties for empirical investigation, such investigation is required to explore these predictions.

Acknowledgements

This research was supported by a grant from the National Institute for Neurological Diseases and Stroke (#R01 NS31824). We are grateful to Laurel Buxbaum and David Glasspool for detailed discussions of the model, Stephanie Warrick for implementational work, Mary Ferraro for cross-checking the validity of an early version of the scoring program, and Glyn Humphreys and two anonymous referees for their invaluable comments and criticisms of early drafts of this paper.

References

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

Boccardi, E., Della Salla, S., Motto, C. & Spinnler, H. (2002). Utilisation behaviour consequent to bilateral SMA softening. *Cortex*, *38*, 289–308.

Botvinick, M., & Plaut, D.C. (2002). Representing task context: Proposals based on a connectionist model of action. *Psychological Research*, *66*, 298–311.

Botvinick, M., & Plaut, D.C. (2004). Doing without schema hierarchies: A recurrent connectionist approach to normal and impaired routine sequential action. *Psychological Review*, *111*, 395–429.

Buxbaum, L.J., Schwartz, M.F., & Carew, 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.

Cooper, R.P. (2002). Order and disorder in everyday action: the roles of contention scheduling and supervisory attention. *Neurocase*, *8*, 61–79.

Cooper, R.P., Shallice, T., & Farringdon, J. (1995). Symbolic and continuous processes in the automatic selection of actions. In J. Hallam (ed.) *Hybrid Problems, Hybrid Solutions*. pp. 27–37. IOS Press, Amsterdam.

Cooper, R.P. & Shallice, T. (1997). Modelling the selection of routine action: Exploring the criticality of parameter values. In M.G. Shafto & P. Langley (eds.), *Proceedings of the 19th Annual Conference of the Cognitive Science Society*, pp. 131–136. Lawrence Erlbaum Associates, Mahwah, NJ.

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

Dehaene, S., & Changeux, J-P. (1997). A hierarchical neuronal network for planning behavior. *Proceedings of the National Academy of Sciences of the United States of America, 94.* 13293–13298.

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

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

Duncan J. (1995). Attention, intelligence, and the frontal lobes. In M.S. Gazzaniga (ed.), *The Cognitive Neurosciences*, pp. 721–733. MIT Press, Cambridge, MA.

Duncan, J., Burgess, P.W. & Emslie, H. (1995). Fluid intelligence after frontal lobe lesions. *Neuropsychologia*, *33*, 261–268.

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.

Forde, E.M.E. & Humphreys, G.W. (2002). Dissociations in routine behaviour across patients and everyday tasks. *Neurocase*, *8*, 151–167.

Fuster, J.M. (1997). *The Prefrontal Cortex* (3rd edition). Raven Press, New York, NY.

Giovannetti, T., Libon, D.J., Buxbaum, L.J. and Schwartz, M.F. (2002). Naturalistic action impairments in dementia. *Neuropsychologia*, *40*, 1220–1232.

Goldberg, G. (1985). Supplementary motor area structure and function: Review and hypotheses. *Behavioral and Brain Sciences*, *8*, 567–616.

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 E. Perecman (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.

Gurney, K., Prescott, T.J. & Redgrave, P. (2001a). A computational model of action selection in the basal ganglia. I. A new functional anatomy. *Biological Cybernetics*, *84*, 401–410.

Gurney, K., Prescott, T.J. & Redgrave, P. (2001b). A computational model of action selection in the basal ganglia. II. Analysis and simulation of behaviour. *Biological Cybernetics*, *84*, 411–423.

Hinton, G.E., & Shallice, T. (1991). Lesioning an attractor network: Investigations of acquired dyslexia. *Psychological Review*, *98*, 74–95.

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

Houghton, G., Glasspool, D.W., & Shallice, T. (1994). Spelling and serial recall: Insights from a competitive queuing model. In G.D.A. Brown & N.C. Ellis (eds.) *Handbook of Spelling: Theory, Process and Intervention*. pp 365–404. John Wiley, Chichester, 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 S. Monsell & J. Driver (eds.) *Control of Cognitive Processes.* Attention and Performance, XVIII, pp. 427–442. MIT Press, Cambridge, MA.

Humphreys, G.W. & Riddoch, M.J. (2003). From vision to action, and action to vision: A convergent route approach to vision, action and attention. In Irwin, D. & Ross, B. (ed.), *Psychology of Learning and Motivation: Visual Cognition, Volume 42.* pp. 225–264. Academic Press, New York, NY.

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.

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

Liepmann, H. (1920). Apraxie. *Ergebnisse der Gesamten Medizin*, *1*, 561–543.

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

McClelland, J.L. (1992). Toward a theory of information processing in graded, random, interactive networks. In D.E. Meyer & S. Kornblum (eds.) *Attention and Performance, XIV*, pp 655–688. MIT Press, Cambridge, MA.

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 R. Davidson, G. Schwartz & D. Shapiro (ed.), *Consciousness and Self Regulation: Advances in Research and Theory, Volume 4*, pp. 1–18. Plenum, New York, NY.

Passingham, R.E. (1993). The frontal lobes and voluntary action. Oxford University Press. Oxford, UK.

Pick, A. (1905). *Studien űber Motorische Apraxie und ihr Nahestehende Erscheinungen: ihre Bedeutung in der Symptomologie Psychopathischer Symptomen-Komplex*. Deuticke, Leipzig.

Poeck, K., & Lehmkuhl, G. (1980). Das syndrom der ideatorischen apraxie und seine localisation. *Nervenartz, 51*, 217–225.

Plaut, D.C., McClelland, J.L., Seidenberg, M.S., & Patterson, K.E. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review, 103*, 56–115.

Plaut, D.C., & Shallice, T. (1993). Deep dyslexia: A case study of connectionist neuropsychology. *Cognitive Neuropsychology*, *10*, 337–500.

Rapp, B., & Goldrick, M. (2000). Discreteness and interactivity in spoken word production. *Psychological Review*, *107*, 460–499.

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. (1990). *Human Error*. Cambridge University Press: Cambridge, UK.

Redgrave, P., Prescott, T.J., & Gurney, K. (1999). The basal ganglia: a vertebrate solution to the selection problem? *Neuroscience*, *89*, 1009–1023.

Rumiati, R.I., Zanini, S., Vorano, L. & Shallice, T. (2001). A form of ideational apraxia as a selective deficit of contention scheduling. *Cognitive Neuropsychology*, *18*, 617–642.

Schwartz, M.F. (1995). Re-examining the role of executive functions in routine action production. In J. Grafman & K.J. Holyoak & F. Boller (eds.), *Structure and functions of the human prefrontal cortex*. (*Annals of the New York Academy of Sciences*, Vol. 769, pp. 321-335). New York: The New York Academy of Sciences.

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.

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

Shallice, T. (2002). Fractionation of the supervisory system. In D.T. Stuss & R.T. Knight (eds.) *Principles of Frontal Lobe Function*, ch. 17, pp. 261–277. Oxford University Press, Oxford, 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.

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.

Stuss, D.T., Shallice, T., Alexander, M.P. & Picton, T.W. (1995). A multidisciplinary approach to anterior attentional functions. *Annals of the New York Academy of Sciences, 769,* 191–212

Verfaellie, M & Heilman, K. M. (1987). Response preparation and response inhibition after lesions of the medial frontal lobe. *Archives of Neurology*, *44*, 1265–1271.

Williams, R.J. & Zipser, D. (1995). Gradient-based learning algorithms for recurrent networks and their computational complexity. In Y. Chauvin & D.E. Rumelhart (eds.) *Backpropagation: Theory, Architectures, and Applications*, ch. 13, pp. 433–486. Lawrence Erlbaum Associates, Hillsdale, NJ.

Yule, P. & Cooper, R.P. (2001). Towards a technology for computational experimentation. In E. Altmann, A. Cleeremans, C.D. Schunn & W.D. Gray (eds.), *Proceedings of the 4th International Conference on Cognitive Modelling*, pp. 223–228. Fairfax, VA. Lawrence Erlbaum Associates.

Yule, P. & Cooper, R.P. (2003). Express: A web-based technology to support human and computational experimentation. *Behaviour Research Methods, Instruments, & Computers*, *35*, 605–613.

Zipf, G.K. (1949). *Human Behaviour and the Principle of Least Effort.* Addison-Wesley, Cambridge, MA.

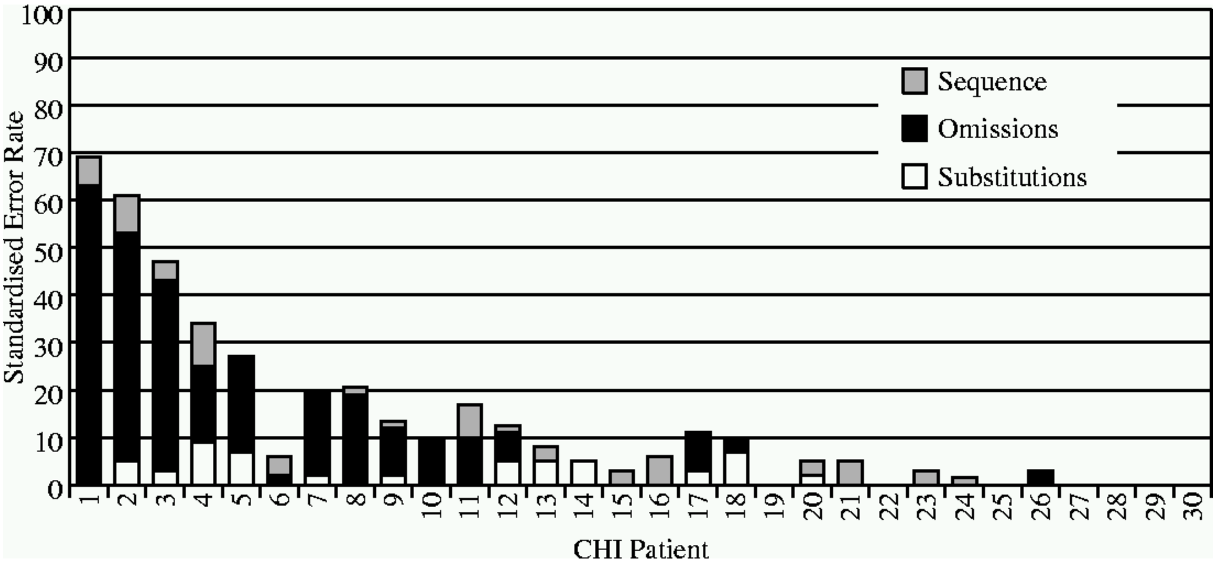

Figure 1: The profile of error types generated by 30 CHI patients on a set of ADL tasks. Errors are standardised such that scores represent errors per 100 opportunities. Patients are ordered from right to left in terms of total error score. Only three of the principal error types are shown. (Adapted from Schwartz *et al.*, 1998.)

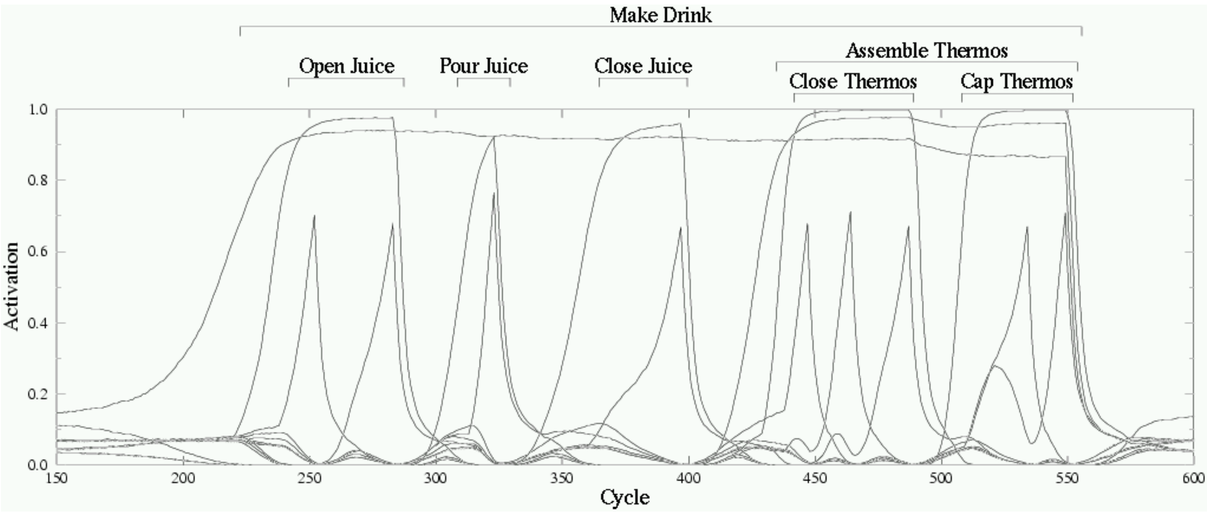

Figure 2: Activation profiles of schema control nodes throughout the subtask of preparing a drink using a juice jar and a thermos. Temporal nesting of component schemas within higher-level parent schemas is shown above the graph. Basic-level schemas are not labelled.

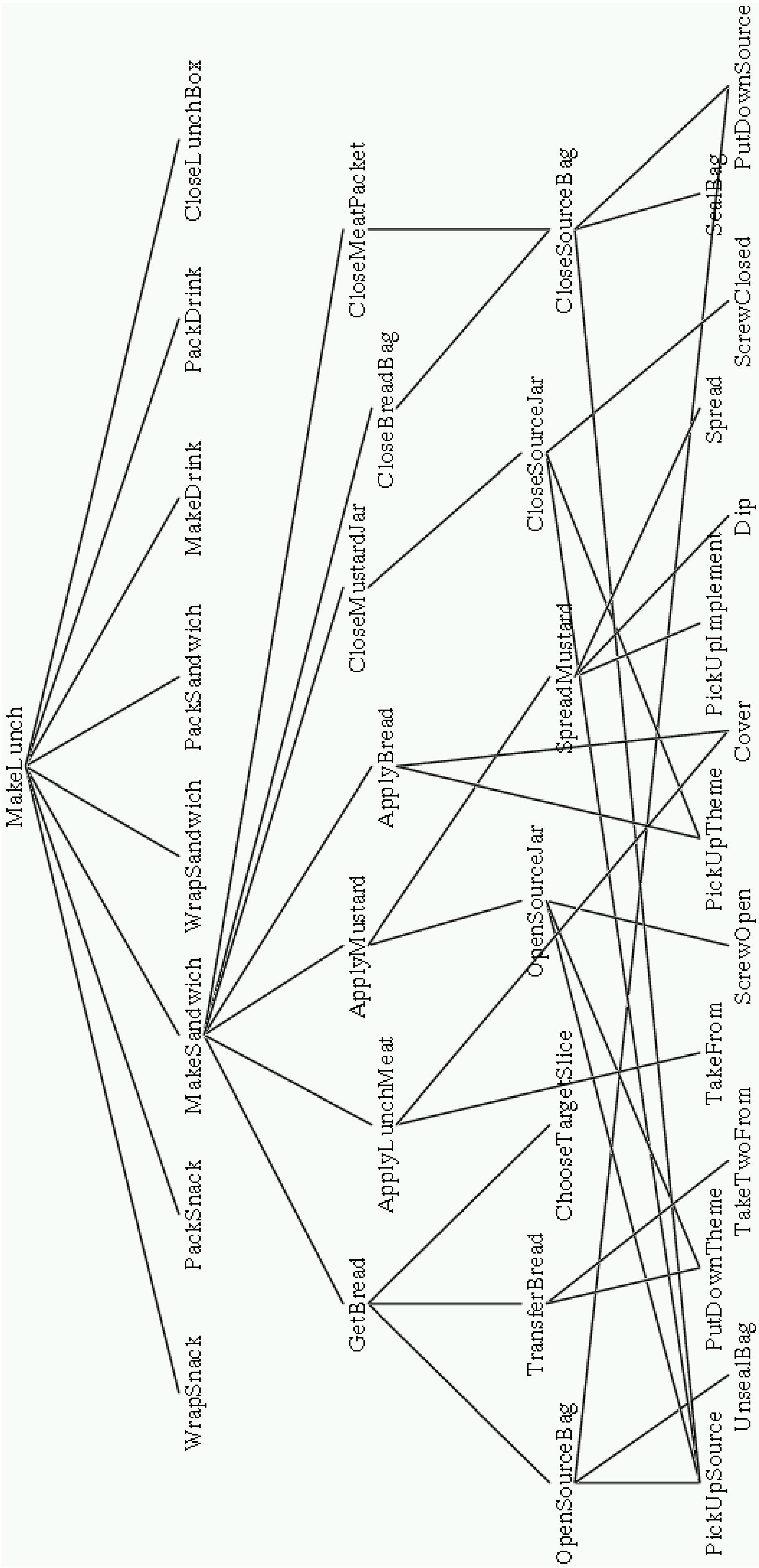

Figure 3: A fragment of the schema hierarchy, as used in the model of the lunch packing task. A complete list of schemas used in the model is given in Appendix A.

+schemaMakeLunch	
+schemaWrapSnack	
+schemaGetFoil	
+schemaPickUpSource	Picking up foilRoll with rightHand
–schemaPickUpSource	
+schemaTear	Tearing from foilRoll with leftHand
–schemaTear	
–schemaGetFoil	
+schemaGetCookie	
+schemaOpenSourceBag	
+schemaPickUpSource	Picking up cookiePacket with leftHand
–schemaPickUpSource	
+schemaUnseal	Discard foilRoll with rightHand
	Unsealing cookiePacket with rightHand
–schemaUnseal	
–schemaOpenSourceBag	
+schemaTakeFrom	Taking cookie4 from cookiePacket with rightHand
–schemaTakeFrom	
–schemaGetCookie	
+schemaWrapCookie	
+schemaCover	Putting cookie4 (held in rightHand) onto foil
–schemaCover	
+schemaWrap	Wrapping cookie4 in foil with rightHand
–schemaWrap	
–schemaWrapCookie	
–schemaWrapSnack	
+schemaPackSnack	
+schemaPickUpTheme	Picking up cookie4Wrapped with rightHand
–schemaPickUpTheme	
+schemaPack	Packing lunchBox with cookie4Wrapped held in rightHand
–schemaPack	
–schemaPackSnack	
+schemaMakeDrink	
+schemaOpenSourceJar	
+schemaPickUpSource	Picking up juiceJar with rightHand
–schemaPickUpSource	
+schemaScrewOpen	Discard cookiePacket with leftHand
	Screwing open juiceJar with leftHand
–schemaScrewOpen	
–schemaOpenSourceJar	
+schemaPourFromJar	
+schemaPour	Pouring juice from juiceJar into thermos
–schemaPour	
–schemaPourFromJar	
+schemaCloseSourceJar	
…	

Figure 4: A segment of well–formed action generated by the model when performing the lunch packing task. Schema name prefixes (+ and –) indicate selection and deselection respectively. Actions performed are shown on the right. In this segment the model selects appropriate actions for wrapping and packing a cookie, before moving on to preparing a drink.

+*schemaMakeLunch*	
+*schemaWrapSnack*	
...	
–*schemaWrapSnack*	
+*schemaMakeDrink*	
...	
+*schemaCapThermos*	
...	
+*schemaPickUpTheme*	Picking up thermosCup with leftHand
–*schemaPickUpTheme*	
+*schemaCap*	Capping thermos with thermosCup held in leftHand
–*schemaCap*	
–*schemaCapThermos*	
–*schemaAssembleThermos*	
–*schemaMakeDrink*	
+*schemaPackSnack*	
+*schemaPickUpTheme*	Picking up cookie4Wrapped with leftHand
–*schemaPickUpTheme*	
+*schemaPack*	Packing lunchBoxLid with cookie4Wrapped held in leftHand
–*schemaPack*	
–*schemaPackSnack*	
+*schemaPackDrink*	
+*schemaPack*	Packing lunchBox with thermos held in rightHand
–*schemaPack*	
–*schemaPackDrink*	
+*schemaMakeSandwich*	
...	
–*schemaMakeSandwich*	
–*schemaWrapSandwich*	
+*schemaPackSandwich*	
+*schemaPickUpTheme*	Picking up sandwichWrapped with leftHand
–*schemaPickUpTheme*	
+*schemaPack*	Packing lunchBox with sandwichWrapped held in leftHand
–*schemaPack*	
–*schemaPackSandwich*	
...	

Figure 5: A lapse in action generated by the model when performing the lunch packing task. After correctly preparing the wrapped snack and the drink, the model picks up the wrapped cookie (while holding the thermos) and packs the wrapped cookie into the lunch box lid (an object substitution error). The thermos is then correctly packed into the lunch box. Later in the task, once the sandwich is made and wrapped, the wrapped sandwich is correctly packed into the lunch box. The lapse was generated with all parameters except noise at their default values. *N*, the standard deviation of normally distributed noise affecting all networks, was set at 0.04.

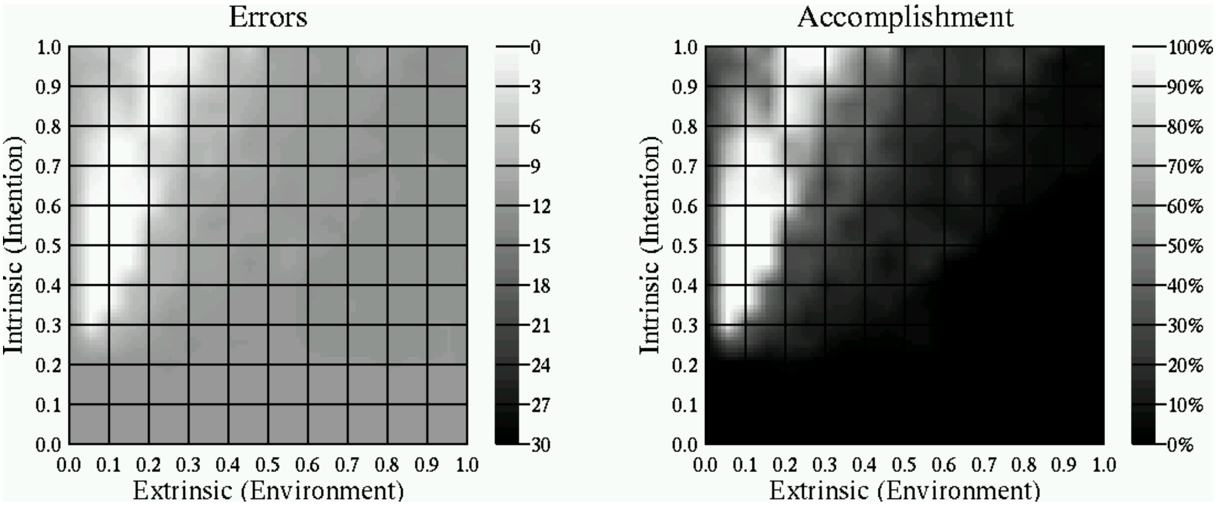

Figure 6: The error surface (left) and accomplishment surface (right) resulting from variation of I_s (intrinsic/intentional excitation within the schema network) and E_S (extrinsic/environmental excitation within the schema network). The model produces error-free behaviour when I_S is moderate to high and E_S is very low.

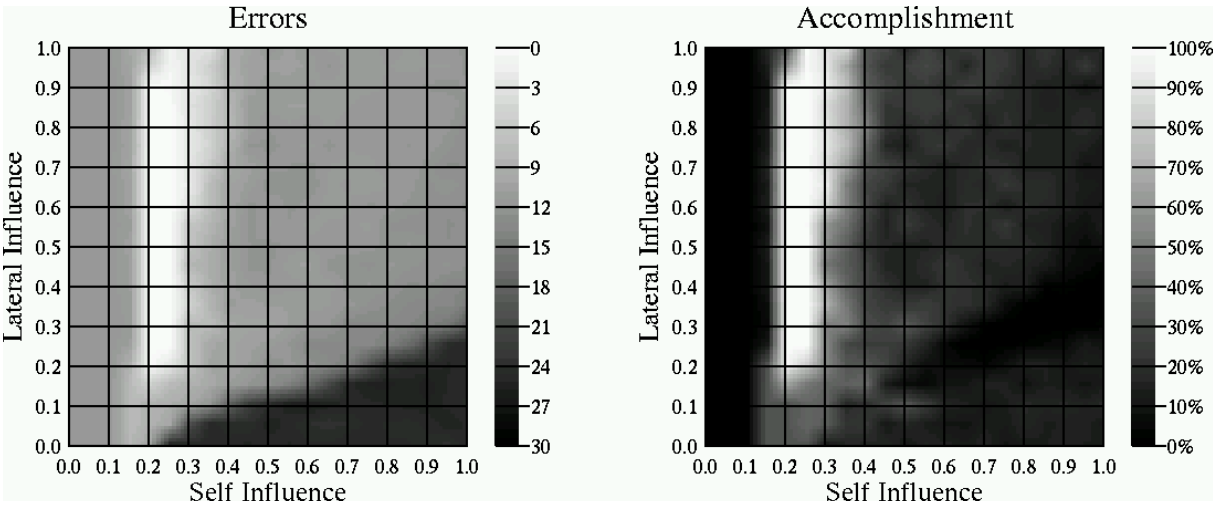

Figure 7: The error surface (left) and accomplishment surface (right) resulting from variation of L (lateral inhibition throughout all networks) and S (self influence throughout all networks). The model produces error-free behaviour for a wide range of values of L when S is between 0.20 and 0.30.

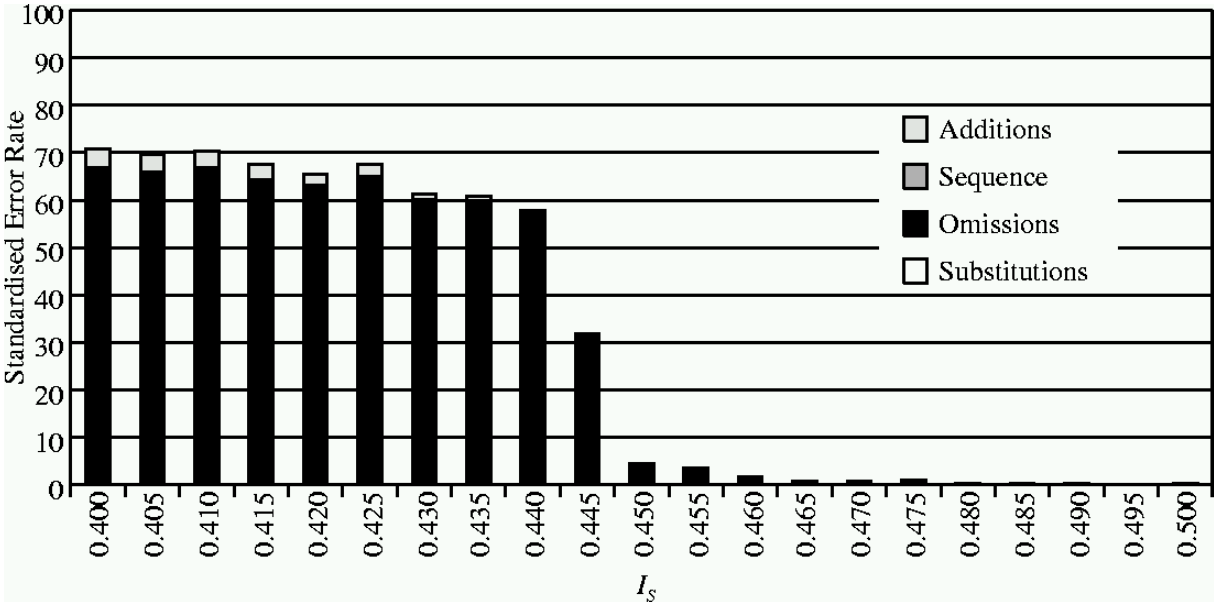

Figure 8: The relative frequency of error types as a function of I_S, the degree of top-down excitation within the schema network. E_S, the degree of bottom-up excitation was simultaneously varied such that $I_S + E_S = 0.600$ as described in the text. (Thus, the horizontal axis could be relabelled with values of E_S decreasing from left to right.) Each bar represents the mean standardised error scores of 100 simulated participants in the distractor absent condition and 100 simulated participants in the distractor present condition.

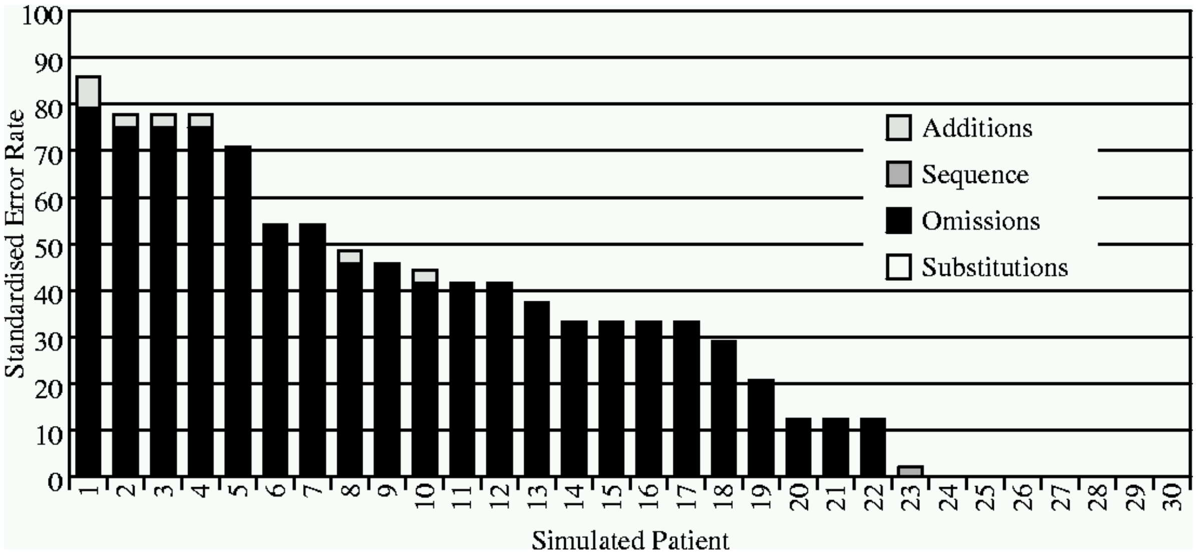

Figure 9: The error profiles of 30 simulated patients. Each bar represents one patient performing the lunch packing task under two conditions, distractors absent and distractors present, with I_s ranging from 0.450 to 0.420. The data were generated from that used in Figure 8, sampled according to the procedure described in the text.

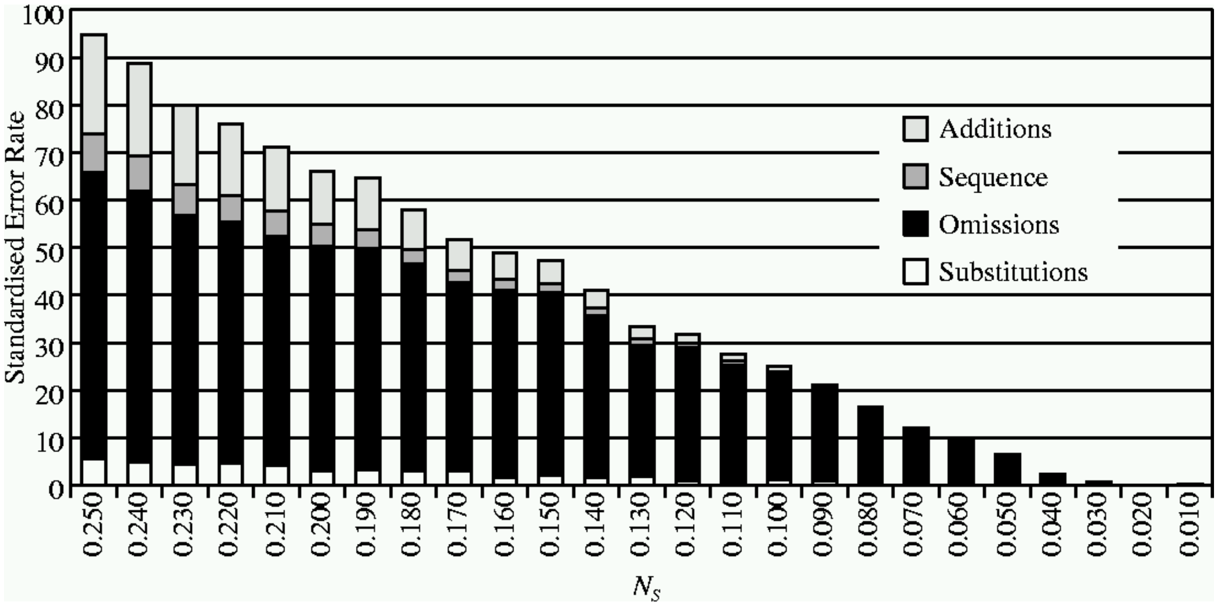

Figure 10: The relative frequency of error types as a function of N_S, the degree of noise in the schema network. Each bar represents the mean standardised error scores of 100 simulated participants in the distractor absent condition and 100 simulated participants in the distractor present condition.

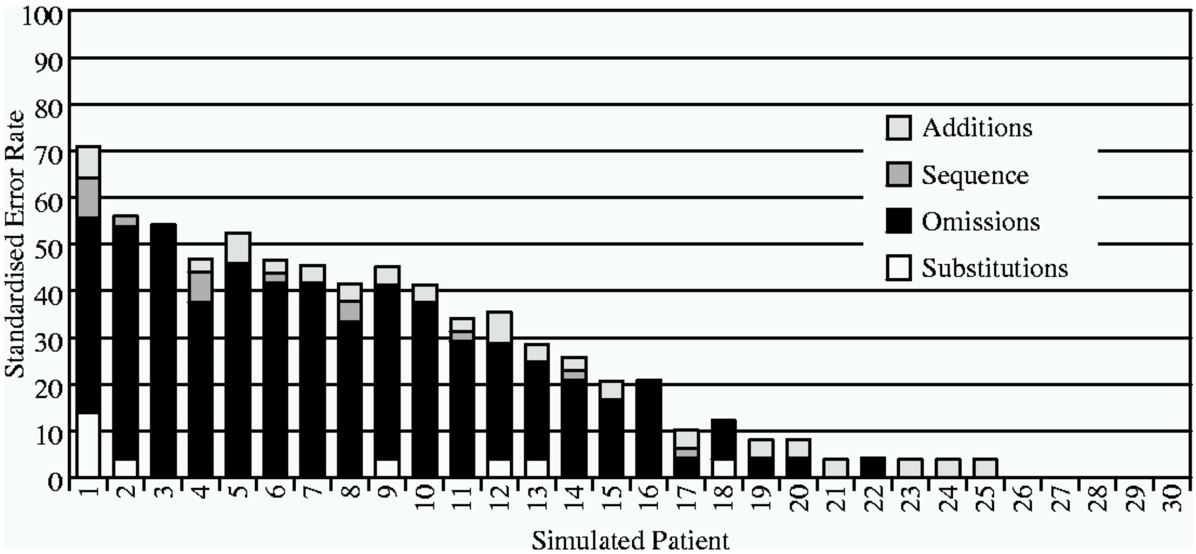

Figure 11: The error profiles of 30 simulated patients. Each bar represents one patient performing the lunch packing task under two conditions, distractors absent and distractors present, with N_S ranging from 0.060 to 0.170. The data were generated from that used in Figure 10, sampled according to the procedure described in the text.

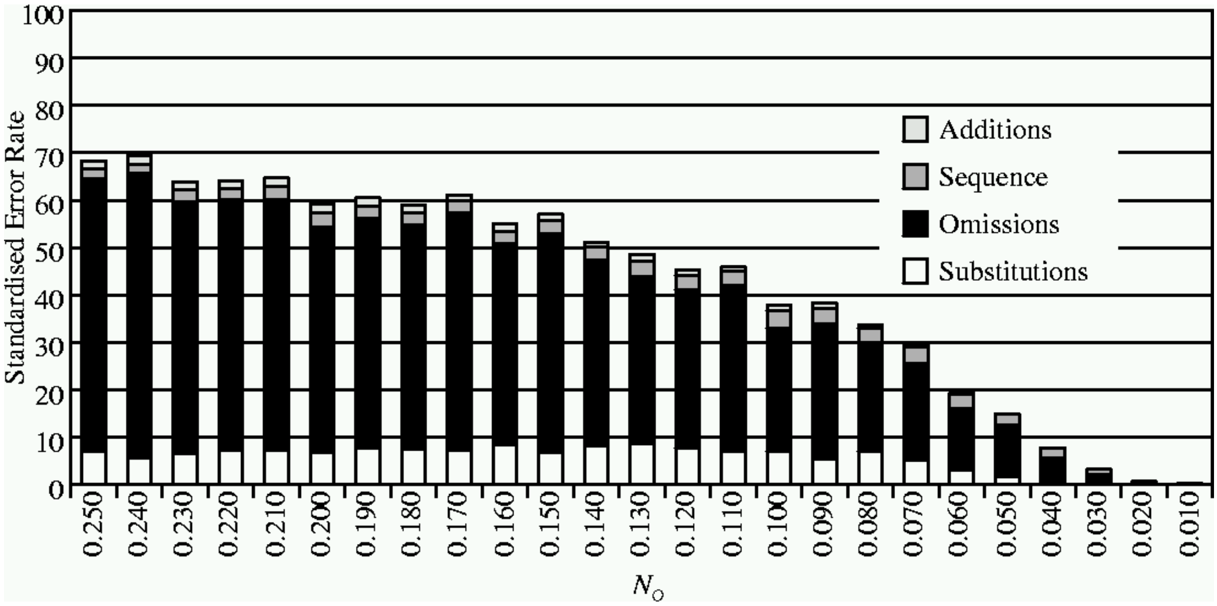

Figure 12: The relative frequency of error types as a function of N_O, the degree of noise in the object representation networks. Each bar represents the mean standardised error scores of 100 simulated participants in the distractor absent condition and 100 simulated participants in the distractor present condition.

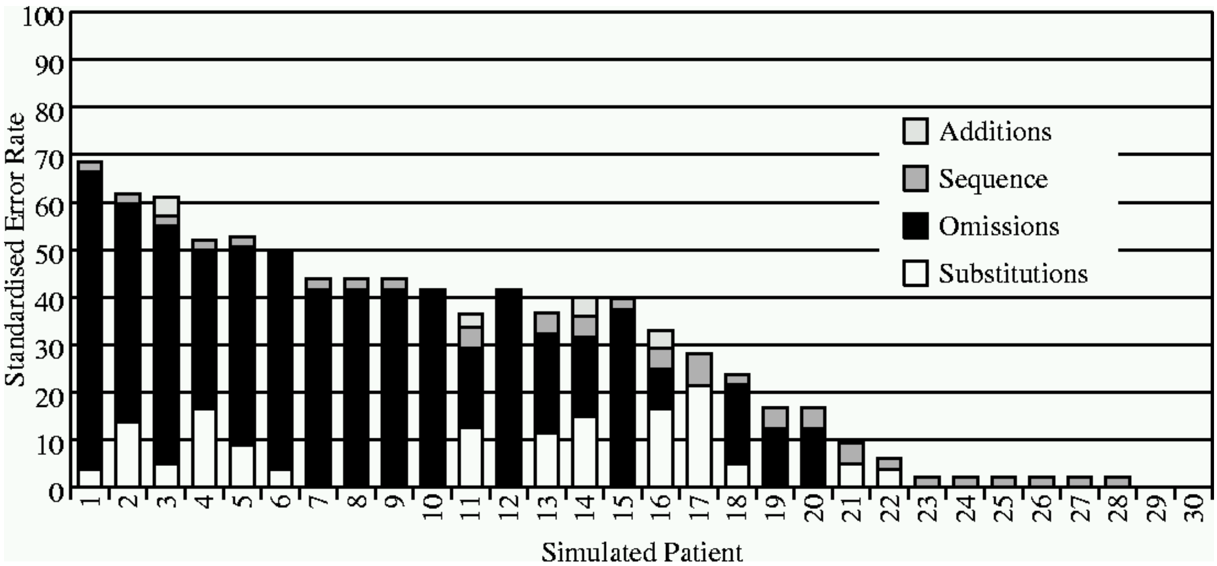

Figure 13: The error profiles of 30 simulated patients. Each bar represents one patient performing the lunch packing task under two conditions, distractors absent and distractors present, with N_O ranging from 0.020 to 0.170. The data were generated from that used in Figure 12, sampled according to the procedure described in the text.

Appendix A: Schemas Used in the Model of the Lunch Packing Task

Below is the complete set of schemas used in the model of the lunch packing task. All schemas are goal-directed (i.e., they achieve a goal).

High-level Schemas

High-level schemas are those that do not correspond directly to actions. Each high-level schema consists of a set of subgoals, and each subgoal has a pre-condition and post-condition. When selected, a high-level schema will excite nodes corresponding to schemas that achieve any of its subgoals, provided the pre-conditions of the subgoal are satisfied and the post-conditions are not satisfied.

schemaMakeLunch achieves goalMakeLunch

Subgoal: goalMakeDrink;	Pre: True;	Post: DrinkPrepared
Subgoal: goalPackDrink;	Pre: DrinkPrepared;	Post: DrinkPacked
Subgoal: goalMakeSandwich;	Pre: True;	Post: SandwichPrepared+TableTidy
Subgoal: goalWrapSandwich;	Pre: SandwichPrepared;	Post: SandwichWrapped
Subgoal: goalPackSandwich;	Pre: SandwichWrapped;	Post: SandwichPacked
Subgoal: goalWrapSnack;	Pre: True;	Post: SnackWrapped
Subgoal: goalPackSnack;	Pre: SnackWrapped;	Post: SnackPacked
Subgoal: goalCloseLunchbox;	Pre: LunchPacked;	Post: LunchboxClosed

schemaMakeDrink achieves goalMakeDrink

Subgoal: goalOpenSourceJar;	Pre: True;	Post: OpenJuiceJarHeld
Subgoal: goalPourFromJar;	Pre: JuiceJarOpen;	Post: FullThermosOnTable
Subgoal: goalCloseSourceJar;	Pre: FullThermosOnTable;	Post: ThermosFull+JuiceJarClosed
Subgoal: goalAssembleThermos;	Pre: ThermosFull+JuiceJarClosed;	Post: ThermosCapped

schemaPourFromJar achieves goalPourFromJar

Subgoal: goalPickUpSource;	Pre: True;	Post: OpenJuiceJarHeld
Subgoal: goalPour;	Pre: OpenJuiceJarHeld;	Post: FullThermosOnTable

schemaAssembleThermos achieves goalAssembleThermos

Subgoal: goalCloseThermos;	Pre: True;	Post: ClosedThermosHeld
Subgoal: goalCapThermos;	Pre: ClosedThermosHeld;	Post: CappedThermosHeld

schemaCloseThermos achieves goalCloseThermos

Subgoal: goalPickUpTarget;	Pre: True;	Post: OpenThermosHeld
Subgoal: goalPickUpTheme;	Pre: True;	Post: LidHeld
Subgoal: goalClose;	Pre: OpenThermosHeld;	Post: ClosedThermosHeld

schemaCapThermos achieves goalCapThermos

Subgoal: goalPickUpTarget;	Pre: True;	Post: ThermosHeld
Subgoal: goalPickUpTheme;	Pre: True;	Post: CupHeld
Subgoal: goalCap;	Pre: ThermosHeld;	Post: CappedThermosHeld

schemaPackDrink achieves goalPackDrink

Subgoal: goalPickUpTheme;	Pre: True;	Post: HoldCappedThermos
Subgoal: goalPack;	Pre: ThermosHeld;	Post: ThermosPacked

schemaMakeSandwich achieves goalMakeSandwich

Subgoal: goalGetBread;	Pre: True;	Post: BreadSlicesDistinct
Subgoal: goalApplyLunchMeat;	Pre: BreadSlicesDistinct;	Post: MeatOnBread
Subgoal: goalApplyMustard;	Pre: BreadSlicesDistinct;	Post: SpreadDoneWith
Subgoal: goalApplyBread;	Pre: Spread+MeatOnBread;	Post: SandwichPrepared
Subgoal: goalCloseBreadBag;	Pre: BreadOnTable;	Post: BreadOnTable+BagClosed
Subgoal: goalCloseMeatPacket;	Pre: MeatDoneWith;	Post: MeatDoneWith+BagClosed
Subgoal: goalCloseSpreadJar;	Pre: SpreadDoneWith;	Post: SpreadDoneWith+JarClosed

schemaCloseBreadBag achieves goalCloseBreadBag

Subgoal: goalCloseSourceBag;	Pre: True;	Post: SourceClosed

schemaCloseMeatPacket achieves goalCloseMeatPacket

Subgoal: goalCloseSourceBag;	Pre: True;	Post: SourceClosed

schemaCloseSpreadJar achieves goalCloseSpreadJar

Subgoal: goalCloseSourceJar;	Pre: True;	Post: SourceJarClosed

schemaGetBread achieves goalGetBread

Subgoal: goalOpenSourceBag;	Pre: True;	Post: BreadBagOpen
Subgoal: goalTransferBread;	Pre: BreadBagOpen;	Post: BreadOnTable
Subgoal: goalChooseTargetSlice;	Pre: BreadOnTable;	Post: SlicesDistinct

schemaTransferBread achieves goalTransferBread

Subgoal: goalTakeTwoFrom;	Pre: True;	Post: BreadHeld
Subgoal: goalPutDownTheme;	Pre: BreadHeld;	Post: BreadOnTable

schemaApplyMustard achieves goalApplyMustard

Subgoal: goalOpenSourceJar;	Pre: True;	Post: OpenMustardJarHeld
Subgoal: goalSpreadMustard;	Pre: OpenMustardJarHeld;	Post: SpreadOnBread

schemaSpreadMustard achieves goalSpreadMustard

Subgoal: goalPickUpImplement;	Pre: True;	Post: ImplementHeld
Subgoal: goalDip;	Pre: ImplementHeld;	Post: SpreadOnImplement
Subgoal: goalSpread;	Pre: SpreadOnImplement;	Post: SpreadOnBread

schemaApplyLunchMeat achieves goalApplyLunchMeat

Subgoal: goalTakeFrom;	Pre: True;	Post: MeatHeld
Subgoal: goalCover;	Pre: MeatHeld;	Post: MeatOnBread

schemaApplyBread achieves goalApplyBread

Subgoal: goalPickUpTheme;	Pre: True;	Post: BreadHeld
Subgoal: goalCover;	Pre: BreadHeld;	Post: BreadOnBread

schemaWrapSandwich achieves goalWrapSandwich

Subgoal: goalGetFoil;	Pre: True;	Post: WrapperOnTable
Subgoal: goalTransferSandwich;	Pre: WrapperOnTable;	Post: SandwichOnOrInWrapper
Subgoal: goalWrap;	Pre: SandwichOnWrapper;	Post: SandwichInWrapper

schemaTransferSandwich achieves goalTransferSandwich

Subgoal: goalPickUpTheme;	Pre: True;	Post: SandwichHeld
Subgoal: goalCover;	Pre: SandwichHeld;	Post: SandwichOnWrapper

schemaPackSandwich achieves goalPackSandwich

Subgoal: goalPickUpTheme;	Pre: True;	Post: WrappedSandwichHeld
Subgoal: goalPack;	Pre: WrappedSandwichHeld;	Post: WrappedSandwichPacked

schemaWrapSnack achieves goalWrapSnack

Subgoal: goalGetFoil;	Pre: True;	Post: WrapperOnTable
Subgoal: goalGetCookie;	Pre: True;	Post: CookieIsPresent
Subgoal: goalWrapCookie;	Pre: Cookie+WrapperArePresent;	Post: CookieInWrapper
Subgoal: goalCloseSourceBag;	Pre: CookieInWrapper;	Post: CookiePacketClosed

schemaGetCookie achieves goalGetCookie

Subgoal: goalOpenSourceBag;	Pre: True;	Post: CookiePacketOpen
Subgoal: goalTakeFrom;	Pre: CookiePacketOpen;	Post: CookieHeld

schemaWrapCookie achieves goalWrapCookie

Subgoal: goalPickUpTheme;	Pre: True;	Post: CookieHeld
Subgoal: goalCover;	Pre: CookieHeld;	Post: CookieOnWrapper

Subgoal: goalWrap;	Pre: CookieOnWrapper;	Post: CookieInWrapper

schemaPackSnack achieves goalPackSnack

Subgoal: goalPickUpTheme;	Pre: True;	Post: WrappedCookieHeld
Subgoal: goalPack;	Pre: WrappedCookieHeld;	Post: WrappedCookiePacked

schemaGetFoil achieves goalGetFoil

Subgoal: goalPickUpSource;	Pre: True;	Post: RollHeld
Subgoal: goalTear;	Pre: RollHeld;	Post: WrapperOnTable
Subgoal: goalPutDownSource;	Pre: WrapperOnTable;	Post: FoilRoll+WrapperOnTable

schemaOpenTarget achieves goalOpenTargetJar

Subgoal: goalPickUpTarget;	Pre: True;	Post: RelevantTargetHeld
Subgoal: goalOpen;	Pre: TargetJarHeld;	Post: OpenTargetJarHeld
Subgoal: goalPutDownTheme;	Pre: OpenTargetJarHeld;	Post: LidNotHeld
Subgoal: goalPutDownTarget;	Pre: True;	Post: NotIrrelevantSourceHeld

schemaOpenSourceJar achieves goalOpenSourceJar

Subgoal: goalPutDownSource;	Pre: True;	Post: NotIrrelevantSourceHeld
Subgoal: goalPickUpSource;	Pre: True;	Post: RelevantSourceHeld
Subgoal: goalOpen;	Pre: SourceJarHeld;	Post: OpenSourceJarHeld
Subgoal: goalPutDownTheme;	Pre: OpenSourceJarHeld;	Post: LidNotHeld

schemaCloseSourceJar achieves goalCloseSourceJar

Subgoal: goalPutDownSource;	Pre: True;	Post: NotIrrelevantSourceHeld
Subgoal: goalPickUpSource;	Pre: True;	Post: RelevantSourceHeld
Subgoal: goalPickUpTheme;	Pre: True;	Post: LidHeld
Subgoal: goalClose;	Pre: SourceJar+LidHeld;	Post: ClosedSourceJarHeld

schemaOpenSourceBag achieves goalOpenSourceBag

Subgoal: goalPutDownSource;	Pre: True;	Post: NotIrrelevantSourceHeld
Subgoal: goalPickUpSource;	Pre: True;	Post: RelevantSourceHeld
Subgoal: goalOpen;	Pre: SourceBagHeld;	Post: OpenSourceBagHeld

schemaCloseSourceBag achieves goalCloseSourceBag

Subgoal: goalPutDownSource;	Pre: True;	Post: NotIrrelevantSourceHeld
Subgoal: goalPickUpSource;	Pre: True;	Post: RelevantSourceHeld
Subgoal: goalClose;	Pre: OpenSourceBagHeld;	Post: SourceBagClosed

Basic-level Schemas

Basic-level schemas correspond directly to actions. They have no subgoals. When selected, basic-level schemas trigger execution of their actions.

schemaPickUpSource achieves goalPickUpSource
schemaPickUpTarget achieves goalPickUpTarget
schemaPickUpImplement achieves goalPickUpImplement
schemaPickUpTheme achieves goalPickUpTheme
schemaPutDownSource achieves goalPutDownSource
schemaPutDownTarget achieves goalPutDownTarget
schemaPutDownImplement achieves goalPutDownImplement
schemaPutDownTheme achieves goalPutDownTheme
schemaScrewOpen achieves goalOpen
schemaUnseal achieves goalOpen
schemaScrewClosed achieves goalClose
schemaSeal achieves goalClose
schemaCap achieves goalCap
schemaTakeFrom achieves goalTakeFrom
schemaTakeTwoFrom achieves goalTakeTwoFrom
schemaChooseTargetSlice achieves goalChooseTargetSlice
schemaPour achieves goalPour

schemaDip achieves goalDip
schemaSpread achieves goalSpread
schemaTear achieves goalTear
schemaCover achieves goalCover
schemaWrap achieves goalWrap
schemaPack achieves goalPack
schemaCloseLid achieves goalCloseLunchbox

Task-Irrelevant Schemas

The model also includes several basic-level schemas that are not needed for completion of the task. These schemas should never be selected under normal operation, but are included to allow the possibility of task-irrelevant behaviour.

schemaSwap achieves goalSwapHands
schemaOpenLid achieves goalOpenLunchbox
schemaFold achieves goalFold
schemaFlip achieves goalFlip
schemaPoke achieves goalPoke
schemaEat achieves goalEat
schemaDrink achieves goalDrink

Appendix B: Objects Used in the Model of the Lunch Packing Task

All simulations included representations of all basic objects in the object representation networks. Simulations of behaviour with distractors also included representations of the distractor objects as given below.

Basic objects and their features

breadBag: IS_BAG | IS_MEDIUM
State: Closed
Contents:
bread0: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM
bread1: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM
bread2: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM
bread3: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM
bread4: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM

cookiePacket: IS_BAG | IS_SMALL, STATE_CLOSED
Contents:
cookie0: IS_EDIBLE | IS_SMALL | IS_DISK
cookie1: IS_EDIBLE | IS_SMALL | IS_DISK
cookie2: IS_EDIBLE | IS_SMALL | IS_DISK
cookie3: IS_EDIBLE | IS_SMALL | IS_DISK
cookie4: IS_EDIBLE | IS_SMALL | IS_DISK

foilRoll: IS_ROLL | IS_CYLINDRICAL

foil: IS_WRAPPER | IS_FLAT | IS_SILVER
Covers *foilRoll*

juiceJar: IS_CUP | IS_SCREWABLE | IS_SIZE2
State: Closed
Contents:
juice: IS_FLUID

juiceJarLid: IS_LID | IS_DISK | IS_SIZE2 | FITS_JAR
Covers *juiceJar*

knife: IS_EXTENDED | IS_TOOL | IS_SHARP

lunchBox: IS_TIN | IS_LARGE | HAS_LID | IS_SQUARE

State: Open

lunchBoxLid: IS_TIN | IS_LID | IS_LARGE | IS_SQUARE
Attached to *lunchBox*

lunchMeatPacket: IS_BAG | IS_MEAT_PACKET
State: Open
Contents:
lunchMeat0: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM | IS_SANDWICH_FILLING
lunchMeat1: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM | IS_SANDWICH_FILLING
lunchMeat2: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM | IS_SANDWICH_FILLING
lunchMeat3: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM | IS_SANDWICH_FILLING
lunchMeat4: IS_EDIBLE | IS_SLICED | IS_SQUARE | IS_MEDIUM | IS_SANDWICH_FILLING

mustardJar: IS_CUP | IS_SCREWABLE | IS_SIZE1
State: Closed
Contents:
mustard: IS_CONDIMENT | IS_EDIBLE

mustardJarLid: IS_LID | IS_SIZE1 | IS_DISK | FITS_JAR
Covers *mustardJar*

thermos: IS_CYLINDRICAL | IS_CUP | IS_SCREWABLE | IS_SIZE4
State: Open

thermosLid: IS_LID | IS_SIZE4 | IS_DISK | FITS_THERMOS

thermosCup: IS_CUP | FITS_THERMOS

Distractor objects and their features

appleSauceJar: IS_CUP | IS_SCREWABLE | IS_SIZE3
State: Closed
Contents:
appleSauce: IS_CONDIMENT | IS_FLUID

appleSauceJarLid: IS_LID | IS_SIZE3 | IS_DISK | FITS_JAR
Covers *appleSauceJar*

glass: IS_CYLINDRICAL | IS_CUP
State: Open

hotDogPacket: IS_BAG | IS_MEAT_PACKET
State: Closed
Contains:
hotDog0: IS_EDIBLE | IS_MEDIUM
hotDog1: IS_EDIBLE | IS_MEDIUM
hotDog2: IS_EDIBLE | IS_MEDIUM
hotDog3: IS_EDIBLE | IS_MEDIUM
hotDog4: IS_EDIBLE | IS_MEDIUM

paperTowelRoll: IS_ROLL | IS_CYLINDRICAL

paperTowel: IS_WRAPPER | IS_FLAT
Covers *paperTowelRoll*

schoolBag: IS_BAG | IS_LARGE
State: Open

spatula: IS_EXTENDED | IS_TOOL

Appendix C: Relation of the Revised Model to that of Cooper & Shallice (2000)

Cooper & Shallice (2000) specified the original interactive activation model of routine action selection in terms of 11 central assumptions, 15 peripheral assumptions, 7 implementational assumptions and a set of equations governing the updating of activations (equivalent to an eighth implementation assumption). The equations governing the update of activations still hold in the extended model, as do the majority of the assumptions. Table 3 shows those assumptions that have changed.

Table 3: Assumptions that differ between the original model of Cooper & Shallice (2000) and the model presented here.

Assumption of original model	*Revised assumption for extended model*
CA2: Schemas consist of a partially ordered set of subgoals	CA2': Schemas consist of a set of subgoals, where each subgoal has an associated pre-condition and post-condition. (Pre-conditions impose an implicit partial ordering on subgoals. Post-conditions allow for optional subgoals.)
CA11: Discrete actions, which correspond to basic-level schemas, specify selection restrictions on the objects and resources to which they may be applied.	CA11': Discrete actions, which correspond to basic-level schemas, specify the functional role of the objects and the state of resources/effectors to which they may be applied.
PA1: Schemas compete if they are alternate means of achieving the same goal or if they share one or more subgoals. This competition is effected by a "lateral influence" on the activations of competing schemas.	PA1': Schemas compete if and only if they share one or more component schemas and neither is a subcomponent of the other. This competition is effected by a "lateral influence" on the activations of competing schemas.
PA5: When all subgoals of a selected schema have been achieved, the schema is inhibited. This inhibition remains in force as long as the schema is selected.	PA5': When all subgoals of a selected schema have either been achieved or have their post-conditions satisfied, the schema is inhibited. This inhibition remains in force as long as the schema is selected.
PA7: The top-down influence on component schemas by selected source schemas is gated by goal precondition achievement. That is, top-down excitation only flows to schemas whose goal has not been achieved but whose pre-condition has been achieved.	PA7': The top-down influence on component schemas by selected source schemas is gated by goal pre-condition and post-condition achievement. That is, top-down excitation only flows to schemas whose goal has not been achieved but whose pre-condition has been achieved and whose post-condition has not been achieved
PA12: Objects and resources are allocated to the arguments roles of discrete actions according to selection restrictions marked on the argument roles of the action and the activation of nodes in the object representation and resource networks.	PA12': Objects are allocated to the unbound arguments roles of discrete actions according to the functional role specifications marked on the argument roles of the action and the activation of nodes in the object representation networks. Resources are allocated to the argument roles of discrete actions according to the state requirements marked on the argument roles of the action and the activation of nodes in the resource network.
IA2: The degree of lateral influence of schema A on schema B (assuming A and B compete) is proportional to the difference between schema A's activation and rest activation. The total lateral influence on a schema is the sum of the lateral influences from all of its competitors.	IA2': The degree of lateral influence of schema A on schema B (assuming A and B compete) is proportional to the difference between schema A's activation and rest activation. The total lateral influence on a schema is the mean of the lateral influences from all of its competitors.

Several additional assumptions relate to object binding. Object binding is a central aspect of the theory, though the unbinding mechanism may be implemented in several different ways. In addition to the original 33 assumptions and the above revisions, the revised model therefore has two additional central assumptions and one additional implementation assumption:

CA12: Schemas may bind objects to one or more functional roles. If a schema binds a functional role, then the first action attempted while the schema is selected that uses an object in that functional role binds the object that is most active for that role to the role. The object remains bound in that role until its activation falls to below that of some other object within the same functional role. It is then unbound.

CA13: If, when an action is executed, one of its argument roles is bound, then the action applies to the object to which the argument role is bound, regardless of activity in the relevant object representation network.

IA8: When a schema that binds an object is deselected, the object representation is inhibited until the object is unbound.

Table 4 shows the values of all parameters in the original and extended model. The use of increased persistence and decreased self influence in the revised model reflects the use of a smaller effective time internal between activation updates. The increased level of lateral inhibition is necessary because the lateral inhibition on a node in the revised model is the mean, rather than the sum, of lateral inhibition from competing nodes. At the same time schema and object representation influences are biased in the revised model slightly more towards non-competitive sources and away from self influence and lateral inhibition. The use of inhibition on deselection within the object representation network means that it is also possible to give more weight to extrinsic influences in the object representation network (i.e., schema to object representation influences).

Table 4: Default parameter values for the original and extended model

Parameter	*Original default value*	*Revised default value*
Rest activation	0.10	0.10
Selection threshold	0.60	0.60
Persistence	0.80	0.87
Noise (standard deviation)	0.001	0.01
Self influence	$S_S = 0.30$; $S_O = 0.30$; $S_E = 0.00$	$S_S = 0.23$; $S_O = 0.23$; $S_E = 0.23$
Lateral influence	$L_S = 0.30$; $L_O = 0.30$; $L_E = 0.00$	$L_S = 0.46$; $L_O = 0.46$; $L_E = 0.46$
Intrinsic / Internal	$I_S = 0.32$; $I_O = 0.00$; $I_E = 0.00$	$I_S = 0.50$; $I_O = 0.00$; $I_E = 0.00$
Extrinsic / External	$E_S = 0.08$; $E_O = 0.04$; $E_E = 1.00$	$E_S = 0.10$; $E_O = 0.40$; $E_E = 0.40$