The Role of Inhibition in Young Children's Performance on the Tower of London: A Computational Study

Frank Baughman

School of Psychology
Birkbeck, University of London

Abstract:

A range of evidence supports the view that processes underlying high-level cognitive tasks are diverse. Miyake et al (2000) offer the possibility of grounding some of these notions in three mechanisms: inhibition, shifting and updating. Indeed, numerous claims indicating a key role of inhibition in problem solving tasks such as the Tower of London (ToL) has accrued. But, explicit accounts of the roles such mechanisms assume are lacking. Using the data from a behavioural study concerned with the problem solving performance of 3-4 and 5-6 year olds on the ToL, a series of four computational models are developed. Their overall aim is to develop and explore one role of inhibition in accounting for differences of performance in younger and older children on the ToL. Performance is evaluated against four criteria: (1) the number of moves made (2) the number of colour balls in the correct place (3) whether the configuration was achieved and (4) whether rule breaks were committed. These measures afford the basis for further specific improvements to be proposed for each successive model and comparisons made against the behavioural data reveal each model to provide a greater degree of fit. The performance of the final two models is found to mirror important qualities of the younger and older children. This paper argues that these data indicate the possibility that younger children's poorer performance on ToL tasks may be a result of their failure to inhibit basic moves, rather than the absence of specific cognitive strategies.

Abstract: 1
1 Introduction & Motivation 3
2 Executive functions and Cognition 4
  2.1 Experimental evidence for EF 5
  2.2 Localisation: Structural evidence of EF in the brain 6
  2.3 Development and deficits of executive functions 7
  2.4 Summary 9
3 Approaches to problem solving 9
  3.1 Psychological approaches 9
    3.1.1 Strategies, goals and subgoals 11
    3.1.2 Integrating a framework of behavioural control (SAS and CS) 12
  3.2 Computational approaches 13
    3.2.1 Soar 14
    3.2.2 ACT-R 15
    3.2.3 The domino model 17
    3.2.4 COGENT 18
    3.2.5 Summary 18
4 Problem solving and the Tower of London: empirical findings 19
5 Modelling the ToL 21
  5.1 A brief preface to the models 21
  5.2 A COGENT approach to the ToL 22
  5.3 Simple Contention Scheduling (CS) model 23
    5.3.1 The Experimenter 24
    5.3.2 The Current State and Desired State 25
    5.3.3 The Subject 25
    5.3.4 Model summary 28
  5.4 Contention Scheduling 'plus' (CS+) model 29
    5.4.1 Organising behaviour 29
    5.4.2 Rule breaks 31
    5.4.3 Model summary 32
  5.5 The 'Younger Child' model 33
    5.5.1 The Subject: introducing supervisory components 33
    5.5.2 Monitoring and Goal Generation 34
    5.5.3 Strategies 34
    5.5.4 Evaluate Solutions 34
    5.5.5 Schema Construction 36
    5.5.6 Belief Update 36
    5.5.7 Model summary 36
  5.6 The 'Older Child' model 38
    5.6.1 Inhibition of immediate moves 38
    5.6.2 Model summary 39
  5.7 Main summary of results 40
6 General discussion 42
References 45
Appendix 1: Summary of Waldau's (1999) study 51
Appendix 2: The six ToL tasks 53
Appendix 3: A printout of the final Older Child model 54

1 Introduction & Motivation

Our ability to reason, plan and solve novel and complex problems is often deemed as what sets us apart from other animals. The study of these behaviours has led to the development of a number of specific questions such as: What are the processes or *mechanisms* that underlie these abilities? How do they *function*? Does some *unitary* component control these processes, or is control *distributed*? The study of these issues is referred to as the study of *executive functions* (EF).

A substantial amount of research attention has focused on the role of three possible mechanisms of EF: (1) *inhibition of prepotent responses* ('inhibition'), (2) *shifting of mental sets* ('shifting') and (3) *updating of working memory* ('updating'). However, the exact conceptualisations of these underlying mechanisms and their levels of theorised involvement in cognition have been open to interpretation and the source of much contention. Miyake, Friedman, Emerson, Witzki, Howerter & Wager (2000) offer one platform from which notions of these mechanisms can be firmly grounded, but studies that explicitly test the roles these mechanisms assume are lacking.

Drawing on a selection of research, the primary goal of this paper is to provide a detailed account of one possible role of inhibition in one commonly used test of problem solving (PS) – the Tower of London (ToL). The view from which this account of inhibition develops is based on a number of influences that exist within the literature on PS and EF that may be considered complementary. This paper will highlight some of these. It will further aim to demonstrate how a combination of their major features can lead to a broader theoretical framework within which the process of PS can be explored and hypothesised mechanisms be assessed more completely. To these ends the use of computational methods are employed.

Within the approach set out here an assumed link between age and the increased ability to inhibit actions is adopted. Examining how these factors interact is not the focus of this paper. Rather, it is to explore the role inhibition may take in accounting for the differences in PS ability at two stages of development. Thus, the account of inhibition offered is *functional* but some of its rationale is derived from developmental literature.

Four computational models of the ToL are developed to explore inhibition with the objective of simulating performance of children in two age groups (3-4 year olds and 5-6 year olds). These models aim to examine how the development of inhibition can account for improved performance on the ToL. The models are therefore motivated by the interests of (a) moving towards a fuller understanding of how underlying processes in cognition may be organised within the mind (b) exploring how these processes may be controlled to produce action and (c) illustrating the effects that maturation of these processes may bring on PS performance.

This paper will begin by offering a general account of what is often meant by the term 'executive functions' and discuss ways in which different approaches have attempted to elucidate our understanding of higher cognitive processes. It will then briefly review some of the main computational approaches to PS before introducing the models of the ToL.

2 Executive functions and Cognition

Broadly speaking, there is little dispute with the view that executive functions (EF) can be described as a set of "general purpose control mechanisms that modulate the operation of various cognitive subprocesses and thereby regulate the dynamics of cognition" (Miyake et al, 2000). Though agreement exists at this general level consensus at a more detailed level has not been established. One source for this disagreement stems from the exact role given over to the 'executive'. Specifically, a fundamental difference in the way EF has been characterised relates to the split between those theorists who argue a view of the executive as a *unitary* component (controlling and regulating behaviour) and those viewing the processes as *diverse* (with the executive merely carrying out instructions it receives).[1] These differing points of view are found expressed in the early writings of Teuber (1972) in his paper *Unity and diversity of frontal lobe functions*; within the influential theories of e.g., Schneider and Shiffrin (1977); and Norman and Shallice (1980). Support for both positions can be found within the literature.

---

[1] Zelazo, Reznick & Frye (1997) illustrate this distinction as the difference between the chief executive officer of a company and the executor of a will.

Given the broader, more open definition of Miyake et al, the study of EF has been available to and associated with a number of approaches, such as cognitive and developmental psychology, neuropsychology and computer science. Each of these disciplines have been influential in shaping the way cognition has been understood and some of the key contributions to this understanding are considered within the following subsections.

2.1 Experimental evidence for EF

A number of tests exist that are believed to load heavily on different cognitive functions. These in turn are taken to consist of various underlying mechanisms. The assumption that these tests measure specific cognitive components is derived from observed dissociations of performance on them. Tests of EF frequently used include, the Stroop test, the Wisconsin Card Sorting Test (WCST), the Tower of Hanoi (ToH) and its variant the Tower of London (ToL), Memory Cards, Random Number Generation, the A-not-B task and the Day-Night task.

Inhibition is typically considered demonstrable by superior performance on tasks where an automatic or dominant response should be suppressed. For instance, this may be the successful inhibition of the tendency to process the semantics rather than the actual colour of word items on the Stroop test. Conversely, a lack in the ability to inhibit is inferred by poorer performance. For example, in a study using the Day-Night task Diamond, Kirkham & Amso, (2002) reported that even when four year olds were *given* a strategy (e.g., say "opposite") performance did not improve. The conclusion they reached was that younger children's performance was adversely affected by their inability to inhibit prepotent responses.

Theorists arguing both sides of the 'unity vs. diversity' debate have used these tests in attempts aimed at explicating the role of EF (see e.g., Rogers & Monsell, 1995; and then, Miyake et al, 2000). However, disputes over their internal validity (see e.g., Phillips, 1997; Rabbit, 1997) and the multitude of possible interpretations that may be taken towards the resulting data have hindered progress. Miyake et al state, "[the] interpretations given to obtained factors often seem quite arbitrary and post hoc" and, given for example the plethora of labels used to describe key factors determining performance on WCST and ToH this appears a valid point. Within the literature terms such as “mental flexibility”, “inhibition”, “mental set shifting”, “planning”, “problem solving” and “categorisation” (see e.g., Bull et al 2001; Miyake et al, 2000) are amongst some of the terms intended to describe the same or similar processes.

With the objective of clarifying some of these issues, Miyake et al (2000) detail a study aimed at determining the extent to which mechanisms of EF are dependent or independent. Using sophisticated analyses[2], Miyake et al find support for the view that the mechanisms of inhibition, shifting and updating are separable thus, bolstering the case for diversity accounts of EF. Consistent with many previous studies and of special relevance to this paper were their findings that inhibition was more strongly associated with performance on the ToH than on a range of other EF tasks. Miyake et al offer one plausible interpretation of these findings, reasoning that in using a simple perceptual strategy in the ToH one is influenced by the tendency to move *towards* greater perceptual similarity rather than move away. This interpretation fits with numerous other studies in which moves that take the configuration of the current state *away* from the goal state are described as ‘counter-intuitive’, or undesirable whilst in fact they are necessary for task completion (Gilhooly, 2002). Thus, the ability to inhibit the tendency to be influenced by such perceptual properties may account for correct performance on tasks where such conflict exists. Equally so, the lack of ability to inhibit this tendency may then account for incorrect performance.

2.2 Localisation: Structural evidence of EF in the brain

Though issues relating to structural accounts of EF are heavily contended, the prefrontal cortex (PFC) has frequently been associated with problems in high-level cognition. Many of the early influences from the modern scientific era on structural accounts of EF came from single case studies of the neurologically impaired [3] and through observing the abnormal behaviour of a patient in life and examining their brain post-mortem. Nowadays, similar aims to localise functions are achieved more efficiently through brain imaging techniques, such as with functional magnetic

---

[2] Miyake et al (2000) use confirmatory factor analyses, arguing it is more sensitive than typical correlational and regressional techniques, at identifying the range of possible underlying relationships.

[3] E.g., the story of Phineas Gage, (a railway worker in the mid-1800’s, injured by an explosion that caused the tool he was using to shoot through his face and out of the top of his head) provided one early source from which notions of localisation developed.

resonance imaging (fMRI), positron emission tomography (PET), single photon emission computed tomography (SPECT) and computerised tomography (CT).[4]

Use of these more recent techniques has produced evidence supportive of a complex and dynamic interaction of mechanisms underlying high-level cognitive processes (Carpenter, Just, & Reichle, 2000). For example, converging evidence for separable and differential levels of involvement of EF mechanisms, as espoused by Miyake et al (2000) has been claimed in a number of fMRI studies (though, see Reitan & Wolfson, 1994). Also focusing on examining the mechanisms of inhibition and shifting, and mirroring those earlier findings, Slyvester et al (2003) report a fMRI study in which they found combined *and* separate patterns of activation within numerous brain areas (e.g. in areas of bilateral parietal cortex, left dorsolateral prefrontal cortex, premotor cortex and medial frontal cortex). These data are consistent with the Miyake et al argument. While the PFC may play a major role in some aspects of EF a range of other diverse processes also appear to contribute to overall functioning within EF tasks.

Though brain-imaging studies may be regarded useful in that they offer further detailed insights into the possible involvement of brain areas in cognition, caution must also be applied. A problem associated with fMRI and other such second order measurements is that areas showing high levels of activity cannot be assumed to be directly involved in the process under study. That is, areas that show activation might only be 'listening' to other areas that are involved directly. The difficulty with this so-called "impurity problem" in discriminating between areas just listening and areas directly involved may be ameliorated by converging evidence from other methodologies.

2.3 Development and deficits of executive functions

A growing body of work focusing on the development of EF points towards the view that EF emerges sooner in childhood than was previously supposed. For example, 2-year olds competence on the A-not-B task is often taken as evidence suggesting early reliance on EF (see e.g., Lehto, Juujarvi, Kooistra & Pulkkinen, 2003; Espy,

---

[4] For general descriptions of the science behind these techniques the reader is referred to Gazzaniga, Ivry & Mangun, (2002), or the excellent online services of www.psychcentral.com or, www.wikepedia.org.

Kaufmann, McDiarmid, & Glisky, 1999), which extends throughout development (see e.g., Hughes, 1998; Zelazo, Carter, Reznick, & Frye, 1997). The importance of EF in cognitive behaviour has also been adopted within more traditional approaches to the study of development. For instance, Russell (1999) proposed a theory of the *executive-Piagetian* in which descriptions of inhibition and working memory mechanisms closely resemble those of Miyake et al, (2000) and occupy central roles in influencing the cognitive development of the child.

Studies of brain maturation also lend themselves to a developmental view of EF. The process of myelination[5] that begins in early childhood and continues into adolescence is found to differ between children of different ages (see e.g., Anderson, 1998) and children of the same ages (Goldman-Rakic, 1987) and is associated with EF performance. Welsh and Pennington (1988) argue that factors controlling myelination in the frontal lobes may therefore be a critical determinant in one's overall cognitive development.

Developmental accounts of EF can be combined with findings from studies of various neurological disorders (see, Shallice & Burgess, 1991). For example, it is frequently reported that patients with damage to the frontal lobes often display no apparent deficits in tests of IQ, or routine actions, but do show significant problems with the regulation and control of behaviour (see e.g., Damasio, 1994; Ozonoff & Jensen, 1999). In these patients, performance may be found to be particularly poor on tasks of EF where a heavy requirement for strategic planning is assumed.

The relationship between deficits in EF and frontal lobe damage has thus been relevant to the study of a number of disorders. For example, the involvement of inhibition, shifting and updating has been studied in autism (see e.g., Griffith, Pennington, Wehner, & Rogers, 1999; Ozonoff & Jensen, 1999; Hughes & Graham, 2002; Mundy, 2003; Hill, 2004), attention-deficit and hyper-activity disorder (see e.g., Houghton, Douglas, West, Whiting, Wall, Langsford, Powell & Carroll, 1999; Koziol & Stout, 1992; Harris, Schuerholz, Singer, Reader, Brown, Cox, Mohr, Chase & Denckla, 1995), learning difficulties (e.g., Bull & Scerif, 2001; Ozonoff & Jensen, 1999), depression (Harvey, Le Bastard, Pochona, Levy, Allilaire, Dubois & Fossati,

---

[5] Myelination refers to the process by which neuronal axons become sheathed in a fatty covering and results in increased speed of transmission between neurons.

2004) and conduct disorder (see e.g., Charman, Carroll & Sturge, 2001). One motivation within the study of these disorders is to establish a better understanding of EF processes. The selective impairment of some functions and the sparing of others may help shed light on this issue.

2.4 Summary

Notions of EF have been shaped by evidence from a number of approaches. This section provides a flavour of some of the key approaches taken to the study of EF and how it relates to complex cognitive behaviour. In light of the variety of studies that have been carried out, the question of the unity vs. diversity of EF mechanisms can be revisited. We may ask "given the range of evidence on offer, are high-level cognitive tasks *likely* to be undertaken by a single unified mechanism?" This paper argues they are not. Rather it appears that the weight of evidence falls in favour of a view in which components of EF are differentially involved in tasks of high-level cognition. Miyake et al provide the foundations on which notions of separable mechanisms can be based, thus allowing the mechanisms of EF to be conceptualised more clearly and the nature of their relationships examined more thoroughly. It is from this position that this paper explores notions of EF with relation to one aspect of high-level cognition, that of problem solving.

3 Approaches to problem solving

In this section, discussions of psychological and computational approaches to problem solving are presented. In the case of the former, a selection of research aimed at establishing a qualitative understanding of the processes that underlie our ability to plan, reason and solve novel and complex problems are considered. In the case of the latter, key elements of computational methods used to explore problem solving are discussed and a rationale for the adoption of one particular approach for modelling the ToL is put forward.

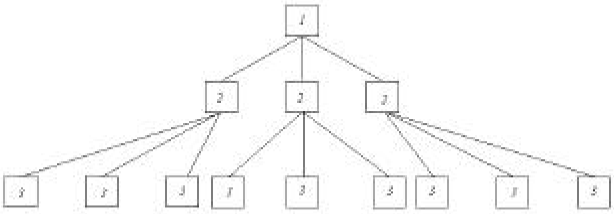
3.1 Psychological approaches

A major contributor to psychological theories of PS was Newell and Simon's seminal work on the General Problem Solver (GPS; Newell & Simon, 1972; see also, Ernst &

Newell, 1969). GPS took the form of a program, however it was initially developed as a theory of human PS. Within the theory, means-ends analysis assumed a key role as a mechanism underlying PS and it worked to reduce the differences between the current and desired states of a problem. The GPS introduced the concept of *problem spaces* (states in which differences could be examined) and *operators* that could be applied to modify these states. All of this was accomplished by simple If-Then rules – called *production rules.*

The idea that problem spaces could be used to represent problems took hold within cognitive theory as it was demonstrated that through expanding the number of possible states contained within the problem space the desired state could eventually be reached. Fig 3.1 illustrates an expanding problem space in which the initial problem state (box 1) can be modified to produce one of three possible outcomes. Each of the three second-level states also yields the possibility for a further three outcomes. The tree grows like this until a branch is found to hold the correct end-state and behaviour can then be guided in order to reach that state.

Fig. 3.1 A state space depicting a growing number of possible outcomes by the third level



Though a reliable method for finding a desired state, constraints placed on this type of processing by memory limitations have encouraged researchers to consider the alternative of heuristics – strategies that aid PS and yet impose fewer demands on cognitive resources. Some of the heuristics examined include e.g., memory manipulation strategies that minimise the cost of switching tasks (Altman & Gray, 1999), goal recursion (Simon, 1975; Altman & Trafton, 1999), simple perceptual strategies (see e.g., Simon, 1975; Altman & Trafton, 1999; Bull, Espy, & Senn, 2004) and look-ahead strategies (Klahr, 1985). The implications some of this work has had for the study of EF are considered next.

3.1.1 Strategies, goals and subgoals

In a formal assessment of the possible processes of PS on the ToH in young children, Klahr & Robinson (1981) report performance differences on tasks ending in different configurations. Specifically, these differences were between tasks ending in a *tower* configuration (tower-ending) and those ending in a *flat* configuration (flat-ending). In these, overall performance was found adversely affected in the latter. One explanation that emerged for these findings related to the degree to which a problem could be broken neatly into unambiguous subgoals. On tower-ending tasks, there is always one disk/ball that must be placed first on the target peg, whereas on flat-ending tasks, there is not necessarily always a particular order for placement of disks/balls. For this reason the subgoal ordering of flat-ending tower tasks has been referred to as ambiguous (see e.g., Klahr & Robinson, 1981; Zelazo, Carter, Reznick & Frye, 1997).

Differences of subgoal ordering in PS have been claimed in a number of studies. For example, several neuroimaging studies have made links between levels of activation and the number of subgoals needed to solve a task (see e.g., Cohen & O'Leary, 1992; Baker, Rogers, Owen, Frith, Dolan, Frackowiak & Robbins, 1996; Morris, Ahmed, Syed & Toone, 1993). Also, Gunzelmann & Anderson (2003) reported that participants increased their planning as it becomes apparent that planning improves their chances of obtaining a correct solution. However, Kotovsky, Hayes & Simon (1985) argued that the effects of task-specific learning and familiarisation may have been overlooked, and Phillips, Wynn, Gilhooly, Della Sala & Logie, (1999) showed that reducing the opportunity for planning did not have a negative effect on PS performance. More importantly, it is unclear how these findings necessarily implicate the use of subgoals and not for instance, increased use of inhibition. Carder, Handley & Perfect, (2004) extend this argument asserting "problem difficulty is a function, not of planning efficiency, but of the ability to successfully inhibit inappropriate move selections at specific points within a solution path" (p1460).

The assortment of results that are reported with regard to the observed patterns of activation indicates that on novel and complex PS tasks there is no consistent involvement of any particular brain area. Instead, activation can be found laterally and bilaterally, and in prefrontal and parietal areas (Carpenter, Just & Reichle, 2000). These conclusions are considered to strengthen the case for diversity views of EF.

Though the use of high levels of resources is required in some novel and complex situations, subgoaling appears too intensive and prescribed a strategy to consider justified. Rather than total reliance on high-resource dependent strategies, a framework that can encompass the range of cognitive tasks we engage in at a number of levels is needed. This is in part what the work of Norman and Shallice attempts to provide.

3.1.2 Integrating a framework of behavioural control (SAS and CS)

Norman and Shallice's (1986) theory of willed and automatic action is perhaps one of the best-known examples to embody the diversity view of cognition. Shallice (1982) considers "models that have only a single selection or general executive component insufficiently powerful to help explain high-level cognitive disorders" (p199).

Originating from research on brain damaged patients the Norman and Shallice framework is one of few grand attempts to provide a complete account of how various distinct cognitive components may interact in producing a range of complex behaviour. It is divisible into two distinct, but significantly related processes that operate according to specific parameters. It comprises a contention scheduling (CS) system and a supervisory attentional system (SAS). Briefly, the CS organises routine behaviours in the form of schemas and is characterised by low-level, predominantly autonomous processes that control everyday actions (for example, in making coffee, see Reason, 1984). The SAS imposes a heavy top-down influence by way of generating goals, creating schemas for CS to carry out and monitoring behaviour. PS and behaviour in general is thus, held to be the product of the influences of these two interrelated systems, with the SAS more involved in novel tasks, but the CS taking over in when tasks become familiar.

The depth and breadth of behaviour the CS-SAS theory is intended to account for has made it a suitable starting point for a number of computational models and its key characteristics find important parallels within several areas. For instance, the distinction between the CS and SAS is roughly analogous to the distinction made between 'Procedural' and 'Declarative' knowledge within cognitive psychology – a distinction often used to reflect the difference between *knowing that* and *knowing* *how*. Similarities also extend to the field of AI. For instance, the layered structure of Norman and Shallice's framework is also found within many 'intelligent agent' architectures (see, Glasspool, 2005).

3.2 Computational approaches

Computational approaches allow models to be developed that can provide accounts of cognitive processes at a number of levels. The specific methodologies that computational approaches assume vary though they share in common the requirement to specify exactly how a model functions. For example, models can be expressed in the form of a spreadsheet, or written as an executable program (e.g., developed in C, or BASIC). Here, one would specify relationships between variables and a set of procedures and then 'run' the program in order to derive values for those variables. The model's performance can thus be evaluated for its overall level of fit with experimental data. In making explicit a models functioning, computational approaches represent an improvement over verbal models, providing a way of evaluating competing theories.

Other methods extensively used include dynamical and connectionist, or neural network approaches (see e.g., Levine, 2000). The advantages of each of these approaches to the study of cognition are debated (see, e.g., Fodor & Pylyshyn, 1988; and, Rumelhart, 1989). However, within the study of high-level cognitive processes the use of production systems have been particularly influential in part because of similarities the production system is assumed to share with the human mind (for example, in terms of supposed similarities in the use of declarative and procedural processes and parallels between stimulus-response and condition-action rules).[6]

In the following sections a brief analysis of the key features of two prominent production system approaches to cognitive processes and one process-driven

---

[6] It is noted that other approaches aimed at the study of high-level processes have been implemented with some success. E.g., Neural networks have been used to simulate performance on PS tasks by Parkinson's patients (Simen, Polk, Lewis & Freedman, 2004); Piagetian tasks (McClelland, 1995; Schultz, 2003); the Stroop task (Cohen, Dunbar and McClelland, 1990); semantic priming and lexical decision tasks (Plaut and Shallice, 1993); and analogical reasoning (Gentner et al., 1995; Thomas, Mareschal and Hinds, 2001).

approach are offered. Next a short introduction to COGENT a non-theoretical approach to modelling high-level processes, is presented.

3.2.1 Soar

Soar is a symbolic approach to dealing with problems within a production system architecture and is a direct descendent of the early work of Newell and Simon's (1972) GPS. Soar[7] was developed from the desire to construct a unified theory of cognition – one that included and could account for the wide range of processes that humans engage in (Newell, 1990). It has been regarded as more than a highly efficient way of organising intelligent action. According to Newell (1990) Soar represents a model of human intelligence.

As with the GPS, the problem space occupies a central position within Soar. Here, elements of a problem are represented, organised and analysed through the use of production rules within 'long-term memory'. When production rules do not cover some part of a task, Soar is said to have reached an *impasse* and attempts to overcome this through a process referred to as *universal-subgoaling*. Here, subgoals are created each with its own problem space and additional searches performed on these.

In its more recent form (see, Newell, 1990) Soar attempts to escape criticisms relating to implausible computational demands (brought on by universal subgoaling) by adopting the *single state principle*. This maintains that only one state is represented in working memory at any one point in time. Thus, relieving working memory of the strain of sifting through multiple problem state spaces. A process of *progressive deepening* in which first superficial and then more intensive searches are performed, guides analysis of this state.

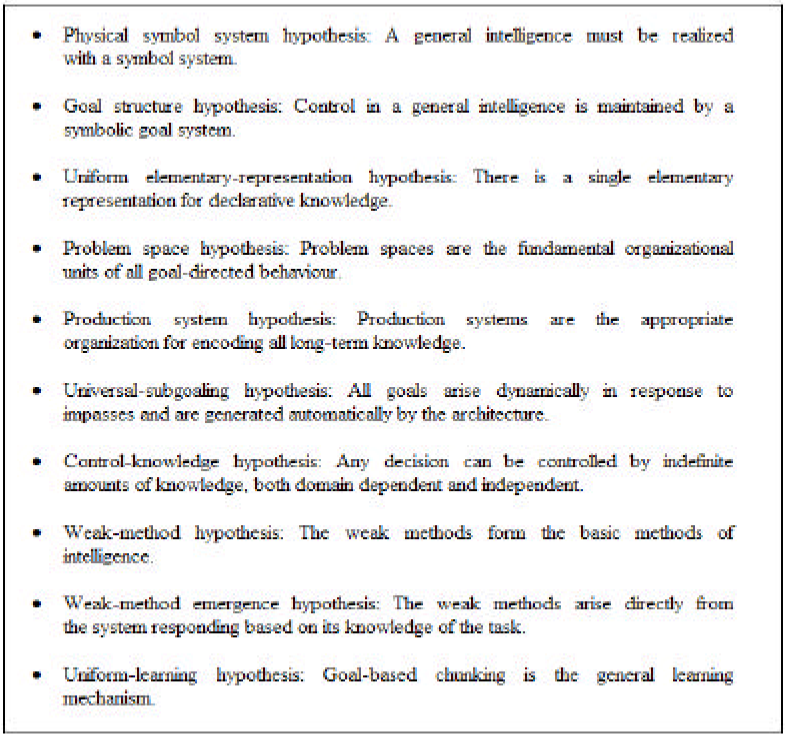
Yet, Soar has failed to convince many of its resemblance to human cognition and a number of serious methodological and theoretical criticisms have been raised (for detailed critque see Cooper & Shallice, 1995). Perhaps the most obvious problem

---

[7] Soar (originally an acronym that stood for State, Operator And Result) functioned by performing extensive searches through problem-spaces and using operators to locate results. Although Soar evolved and its architecture changed, leaving the problem space with less of a significant role, its name remained.

relates to the great number of theoretical assumptions that underlies it (see table 3.2 below).

<u>*Table 3.2. Hypotheses underlying Soar*</u>



- Physical symbol system hypothesis: A general intelligence must be realized with a symbol system.
- Goal structure hypothesis: Control in a general intelligence is maintained by a symbolic goal system.
- Uniform elementary-representation hypothesis: There is a single elementary representation for declarative knowledge.
- Problem space hypothesis: Problem spaces are the fundamental organizational units of all goal-directed behaviour.
- Production system hypothesis: Production systems are the appropriate organization for encoding all long-term knowledge.
- Universal-subgoaling hypothesis: All goals arise dynamically in response to impasses and are generated automatically by the architecture.
- Control-knowledge hypothesis: Any decision can be controlled by indefinite amounts of knowledge, both domain dependent and independent.
- Weak-method hypothesis: The weak methods form the basic methods of intelligence.
- Weak-method emergence hypothesis: The weak methods arise directly from the system responding based on its knowledge of the task.
- Uniform-learning hypothesis: Goal-based chunking is the general learning mechanism.

(Taken from Laird, Newell & Rosenbloom, 1987.)

3.2.2 ACT-R

Anderson (1983) and Anderson & Lebiere's (1998) ACT-R is a cognitive architecture that assumes the distinction characterised by declarative vs. procedural knowledge (often associated with explicit vs. implicit memory). That is, the structure of ACT-R dictates that a mix of declarative and procedural processes underlie cognitive behaviour. In ACT-R, declarative knowledge consists of a collection of facts, or knowledge about things, objects and places. For instance it might consist of the fact that Paris is the capital of France.[8] Procedural knowledge corresponds to knowledge of *how* something is done, but is assumed to take a different form. For instance, we may have the ability (and knowledge) of how to ride a bike yet this knowledge is difficult to translate, or articulate explicitly.

---

[8] It is noted that declarative knowledge does not necessarily represent *truths*, but rather *true beliefs*. For instance, the wrong belief that the capital of France is Lyon, would also constitute 'knowledge' within this distinction.

To represent knowledge about things in declarative knowledge, *chunks* are used to encode information and a system of activation whereby information about when the chunk was last used and how it fits with the current situation is accessed. These and levels of activation govern the process of retrieval of individual chunks. It is due to these properties that ACT-R is considered a hybrid system, combining elements of symbolicism and connectionism. Within procedural knowledge, 'production rules' consisting of *condition* and *action* sides are used to represent procedural knowledge. The firing of an action (the 'then' component of the rule) is reliant upon any associated conditions being met.

For example,

```
If the Goal is to give the capital of F
      And P is in the database of facts as the capital of F
Then, give P as the answer
```

In declarative knowledge, the following chunk that encodes the fact that Paris is the capital of France might exist.

```
isa capital_fact
country France
city Paris
```

ACT-R has been used to model a vast number of cognitive phenomena, within areas such as perception and attention, learning and memory, problem solving and decision-making and language processing.[9] However, a key structure within ACT-R, referred to as the *goal stack* which functions to hierarchically store the goal and subgoals of a problem, has been challenged (see e.g., Altman & Trafton, 1999).

Some specific criticisms relate to the efficiency with which the goal stack enables PS to be carried out and ACT-Rs lack of ability to account for forgetting of old goals. That is, as subgoals are identified they are 'pushed' to the goal stack and once all the necessary subgoals have been established it is simply a matter of selecting the top item to deal with. As each item is completed, it is 'popped' off the stack to reveal the next subgoal to complete. Thus, the goal stack predicts minimum reliance on resources and maximum efficiency on problems and this is often what is demonstrated.

---

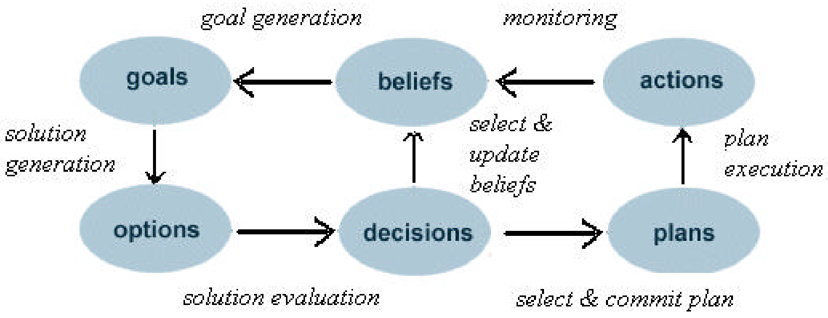
[9] See http://act-r.psy.cmu.edu/publications for a more detailed list of topics investigated.

For these reasons it is argued the goal stack is too good a mechanism to be considered plausible in human PS. Altman and Trafton (1999), claim "evidence suggests that memory for pending goals is strategic and effortful rather than perfect and automatic" (p2) arguing a more parsimonious *limited stack* (maximum of two items) is equally sufficient to enable accurate PS.[10]

3.2.3 The domino model

Fox and Das' (2000) domino model (see figure 3.3) has been used extensively in AI work on expert systems. Its relevance here is due to both general and specific similarities it shares with the work of Norman and Shallice (1986).

Figure 3.3. The generalised domino model of Fox & Das (2000)



Glasspool (2005) and Glasspool and Cooper (2002) highlight a number of similarities between surface features and the tasks that components are engaged in. For example, in each model the top level pursues goal generation, monitoring and evaluation of behaviour and the middle layers are each given over to triggering actions.

The domino model is not assumed to be a model of human PS as it was developed outside of constraints imposed by psychological theory. As a process however it represents a highly organised and efficient way of tackling problems and has been utilised within a number of applications (e.g., in medical decision support).

---

[10] This point is echoed by Fox (2005) who argues that not only does ACT-R remain too firmly rooted in explanations at the production rule level, but that none of the supposed mechanisms underlying ACT-R have been proved *necessary*.

3.2.4 COGENT

Developed by Cooper and Fox (1998) and Cooper (2002) COGENT (an acronym for Cognitive Objects in a Graphical EnviroNmenT) provides a bridge between 'box-and-arrow' type representations of cognitive processes and the typical computer languages used to implement them (e.g., Lisp or Prolog). COGENT combines qualities of both. That is, the graphical environment enables flow diagrams of a process to be constructed and a rule-based language, employing Prolog then used to flesh out each components functioning.

Within the COGENT environment a number of standard boxes are available (discernible by their different shapes). These include for example, *buffers*, *rule-based processes*, *connectionist networks* and *data* and *table sinks* that can be dropped on to a canvas and their connections to other boxes specified through 'read' and 'write' arrows.

The point of emphasis here is that in contrast to Soar and ACT-R, COGENT does not specify any particular theoretical architecture within which models must be placed. It supports the exploration of different computational perspectives and is capable of incorporating both connectionist and symbolic features within the same model (see Cooper, 2002; Cooper & Fox, 1998). Thus, the subject of PS can be taken up within COGENT without importing unwanted or additional theoretical influences.

3.2.5 Summary

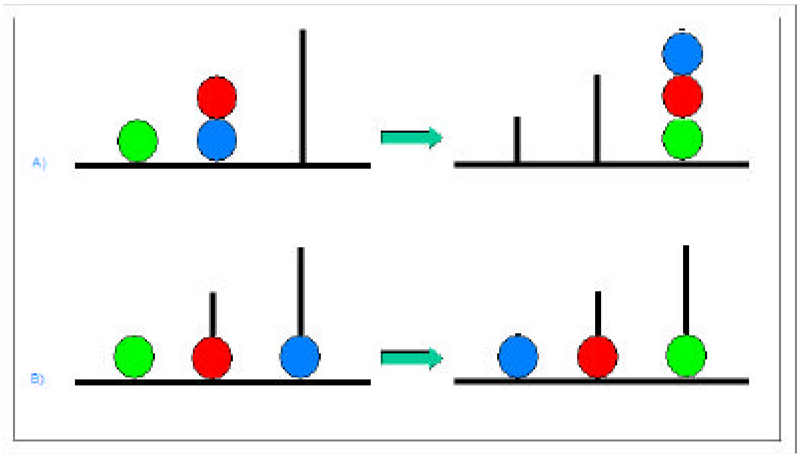
The aim of this section was to present key strengths and weaknesses of some of the computational approaches taken towards the study of PS. Whilst throughout Soar's development efforts have been made to avoid problems of memory limitations, it remains too heavily dependent on a number of assumptions. The concerns of ACT-R on the other hand, geared more towards the use of semantic learning is argued fails in part because of the implausible demands it makes on resources. The domino model, although an efficient way of tackling decision-making claims no direct psychological links. COGENT however offers the possibility of developing a model without calling on any implicit, built-in assumptions. For these reasons it is considered that COGENT offers the most suitable environment within which the objectives discussed throughout this paper can be implemented in a model of the ToL.

4 Problem solving and the Tower of London: empirical findings

Derived from the Tower of Hanoi and originally introduced by Shallice (1982), the ToL has become a popular tool for measuring PS abilities of children and the neurologically impaired. The number of possible states and the physical constraints imposed by the apparatus of the two tasks indicate they are not isomorphic (see e.g., Bull, Espy & Senn, 2004). However, they have both been held to load heavily on EF and, in the case of the ToL in particular, on *inhibition* (Miyake et al, 2000; Bull, Espy & Senn, 2004).

Figure 4.1 below provides two examples of a 3-move problem, on the ToL task. Figure 4.1a, illustrates a typical tower-ending problem, figure 4.1b a flat-ending problem.

Figure 4.1. Tower-ending and flat-ending 3-move ToL problems



A brief summary of some key, consistent findings from a selection of studies are presented here as the basis from which the computational models are developed. This necessarily includes a range of influences that address (1) the behaviours and strategies assumed to be employed by children, and (2) the criteria applied to assess performance. Each of these is considered next.

A considerable amount of research has focused on establishing the extent to which either more simple strategies (such as direct perceptual biases) or, more elaborate strategies (such as means-ends analysis and look-ahead n-moves) influence PS behaviour. The general pattern of findings suggests means-ends analysis is too sophisticated and intensive a strategy to consider plausible for PS in children. Look-ahead moves appear to gain more credibility within the literature. This is evidenced by observations that children are able to move one object to an alternate location in order to reach a second (e.g., Klahr & Robinson, 1981; Gratch, 1975; Klahr & Wallace, 1976). Another feature of younger children's performance is the apparent difficulty they display on more complex problems. A trait that Klahr and Robinson (1981) suggest is a product of being overly influenced by superficial features of the problem.

Running the six ToL tasks[11] on 17 children aged 3-4 and 19 children aged 5-6 years produced the following findings:

(1) Older children produced more complete solutions compared to the younger children

(2) Within each age group there was little difference in performance on tower-ending vs. flat-ending tasks

(3) Increase in age was associated with increase in performance on tower-ending, but not flat-ending tasks

From the research on the ToL it is possible to extract two strategies that young children may use in PS. These are used to form specific components within the computational models developed here. The strategies suggested by previous work include (1) an *immediate-hit* strategy (the tendency to place a ball in its target position immediately if the target-position is free and the target-ball is free to move) and (2) a *one-move look-ahead* strategy (the ability to plan moves up to one-move away). See e.g. Bull et al, 2004; Goel, Pullara & Grafman, 2001.

A second issue of importance in developing these computational models is to specify the criteria that are to be used to evaluate their performance. On this, the literature reveals the ToL is typically measured using data on (a) whether the correct solution was reached and (b) whether the solution was achieved within the minimum number of moves (and quite often this does not include a record of the actual number of moves made. See e.g., Bull, 2004). However, re-analysis of the experimental data used within the original study reveals these may not be the best nor, the only measurements of performance. Specifically, two features of young children's behaviour appear to have often been over-looked. These are *rule breaks* (e.g., moving two balls at a time) and *partial-completion* (e.g., only one or two balls are in their correct positions). Incorporating these variables into an assessment of PS may allow a more detailed understanding of young children's abilities on the ToL and provide for a fuller model of behaviour.

5 Modelling the ToL

5.1 A brief preface to the models

In the remainder of this paper I will set out to achieve the following:

1) Construct a series of models within which the ToL can be carried out. The influences of which are derived mainly from the following work:
    i) Norman and Shallice's (1986) framework of automatic and controlled behaviour
    ii) The Fox and Das (2000) domino model
2) Use these models to demonstrate the effects of simple and elaborate strategies on PS performance and assess the degree to which they sufficiently account for children's actual behaviour
3) Provide a role of inhibition within a model that accounts for the differences in performance observed between children aged 3-4 and children aged 5-6 years old.

Performance will measured against the following four criteria:

- Total number of moves
- Correct solutions
- Number of balls in place
- The proportion of rule breaks committed

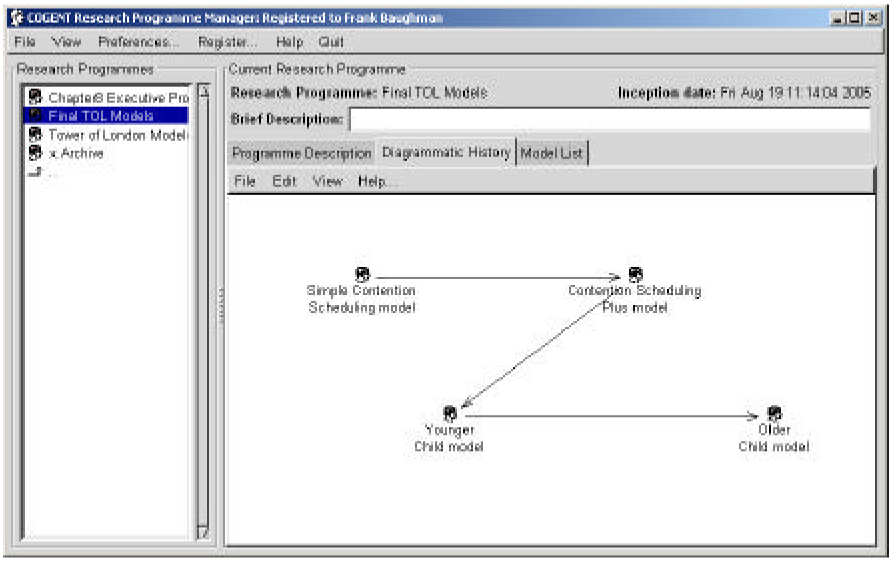
---

[11] Each problem within the two sets of three required a minimum of 3, 4, & 5 moves, respectively to complete the task. Increased number of minimum moves being roughly equated with increased level of difficulty (see Shallice, 1982).

5.2 A COGENT approach to the ToL

Displayed below at the Programme Manager level in COGENT are the series of models of PS on the ToL (figure 5.1). They are: (1) a simple Contention Scheduling (CS) model, (2) a Contention Scheduling 'plus' (CS+) model (3) a Younger Child model and (4) an Older Child model. As in the behavioural study each model was run on all six tasks for a total of 17 pseudo-subjects. They each take as their problem-set the 3 tower-ending and 3 flat-ending tasks[12] used in the original study (Waldau, 1999).

Figure 5.1 The four COGENT models



Research Programme: Final TOL Models

Inception date: Fri Aug 19 11:14:04 2005

Brief Description:

The overall aim for the first two models is to variously demonstrate performance of two PS systems that rely exclusively on direct perceptual processes. The latter two models are aimed at simulating more completely the data of 3-4 and 5-6 year olds (e.g., including rule breaks) and integrating a mechanism of inhibition (Miyake et al, 2000), within a framework based on the work by Norman & Shallice (1986) and Fox and Das (2000).

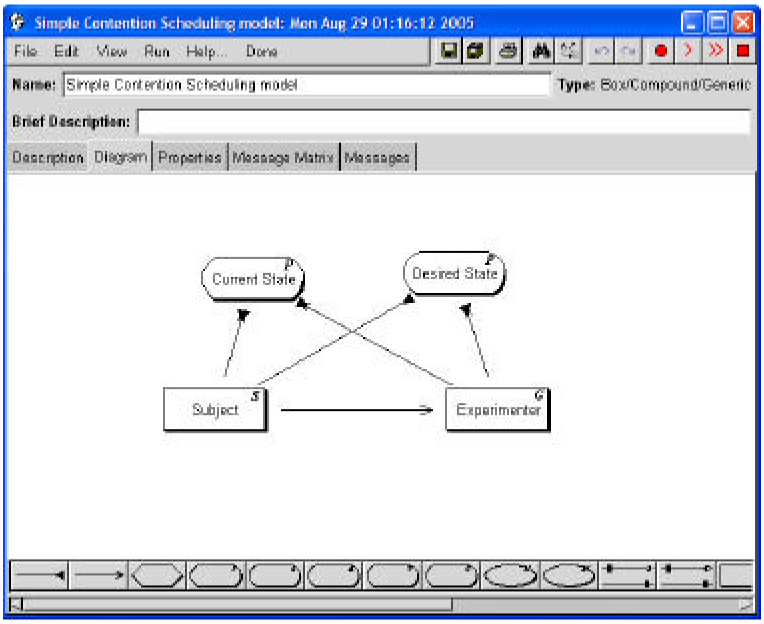
---

[12] Tasks are included for reference, in appendix 2

5.3 Simple Contention Scheduling (CS) model

The Simple CS model was developed to operate solely on information derived from gross physical properties of the ToL. Because no strategies adorn this model it is capable only of picking up and moving balls at random. As per the rules of the task the model is constrained to moving one ball at a time. At the top level (and common to each model), the main components are presented in figure 5.2. They are the **Experimenter** and **Subject** and the **Current State** and **Desired State**.

Figure 5.2 The main experimental components



Simple Contention Scheduling model: Mon Aug 29 01:16:12 2005

Name: Simple Contention Scheduling model

Type: Box/Compound/Generic

Brief Description:

The Experimenter sets up and analyses each ToL task. Thus, the Experimenter must send, or ‘write’ information to the Current and Desired states so that the start state and end state are available to the Subject. On completion, the Experimenter also ‘reads’ those states to assess how close each PS attempt was at reaching the goal state.[13]

The Subject need only read from the Desired State, but because it acts directly on the environment, it must also be able to read and write to the Current State. Finally, it must be able to send a message to the Experimenter to signal completion of a task.

---

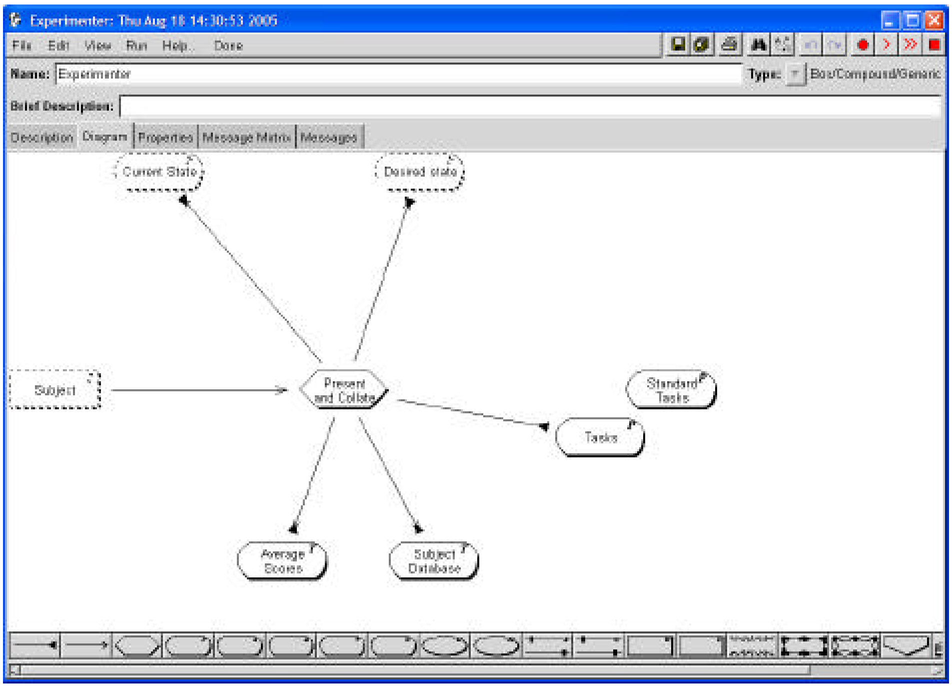
[13] Standard arrow heads represent a ‘write’ process, the filled triangular heads represent a ‘read’ processes. For further specific detail relating to COGENTs design environment the reader is referred to Cooper (2002) and Cooper & Fox (1998).

5.3.1 The Experimenter

The internal structure of the Experimenter is shown in figure 5.3. At the centre of this figure **Present and Collate** serves as the input/output process for the Experimenter's interaction with the Subject and the environment. It takes problems from Tasks and sends them to the Current and Desired states. On completion of a task, it feeds data through to two buffers (**Subject Database** and **Average Scores**) that calculate information pertaining to:

- The *number of moves* taken to complete the problem
- The number of *balls in correct place*
- Whether the end *configuration* was correct
- Whether the Subject performed any *rule breaks*

Figure 5.3 The Experimenter components



Name: Experimenter

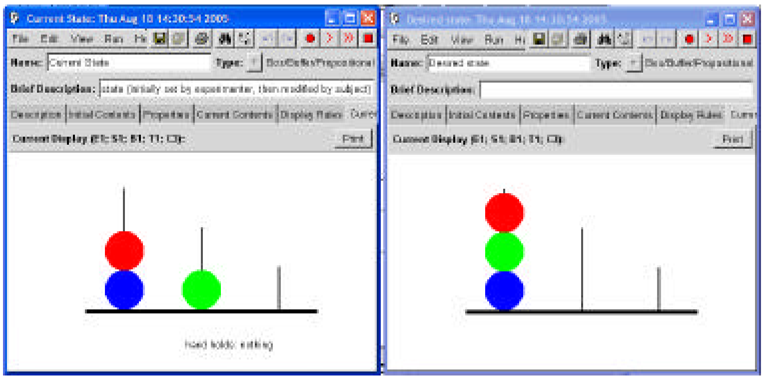
Type: Box/Compound/Generic

Brief Description:

5.3.2 *The Current State and Desired State*

The physical attributes of the ToL are represented in visual form in the Current and Desired states (see figure 5.4). The Current State (pictured left) shows the starting position. Throughout each task, the Desired State remains static, as the Subject is performing no actions on it. But, whenever actions such as taking away or putting down a ball are performed, the contents of the Current State are instantly updated.

Figure 5.4 Current and Desired states



Name: Current State

Type: Box/Buffer/Propositional

Brief Description: state (initially set by experimenter, then modified by subject)

Current Display (E1; S1; B1; T1; C1):

Hand holds: nothing

Name: Desired state

Type: Box/Buffer/Propositional

Brief Description:

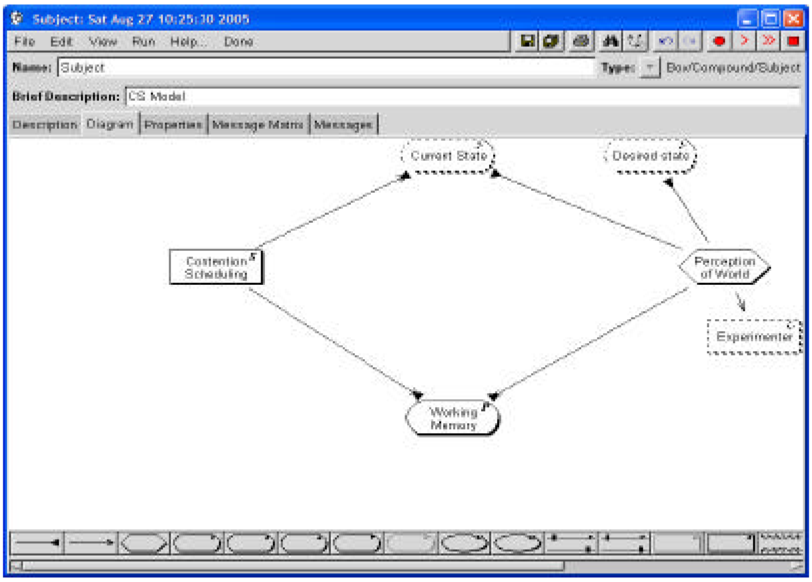
Current Display (E1; S1; B1; T1; C1):

5.3.3 *The Subject*

In figure 5.5, the Subject derives representations of the Current and Desired states through **Perception of World**. This process deals with extracting simple properties of the task and maintaining representations of these states in Working Memory.

Processes within **Contention Scheduling** identify (1) the balls that can be moved and (2) the pegs that have space, by reading from the Current State. The final outcome of which ball to move and which peg to place it on is the result of competition between nodes within an *interactive activation-based network* in Contention Scheduling.

Figure 5.5 The Subject



Subject: Sat Aug 27 10:25:30 2005

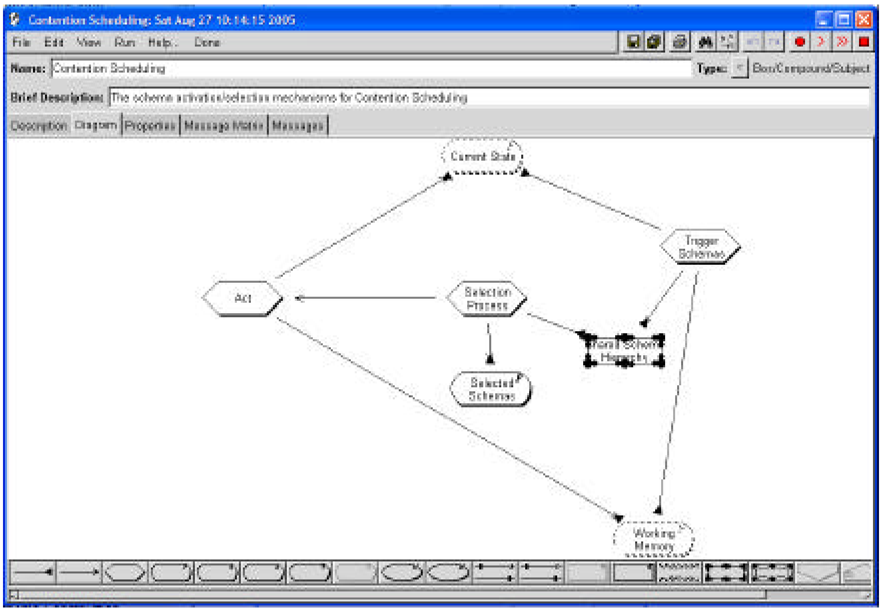
Name: Subject

Type: Box/Compound/Subject

Brief Description: CS Model

Figure 5.6 below illustrates the processes within Contention Scheduling in which action schemas (such as ‘pick up green’ and ‘put down on centre peg’) are ultimately produced. For each ball that can be moved, **Trigger Schemas** sends an excitatory message to the corresponding node in **Shared Schema Hierarchy**. When the level of activation for a node reaches its threshold (0.75) that action is selected and carried out through **Act**.

Figure 5.6 The contention scheduling process



Contention Scheduling: Sat Aug 27 10:14:15 2005

Name: Contention Scheduling

Type: Box/Compound/Subject

Brief Description: The schema activation/selection mechanisms for Contention Scheduling

The role of Trigger Schemas is to select balls that are free and place them on pegs that have space. This is achieved through Rules 2 and 4, 5, and 6 respectively, of excerpt

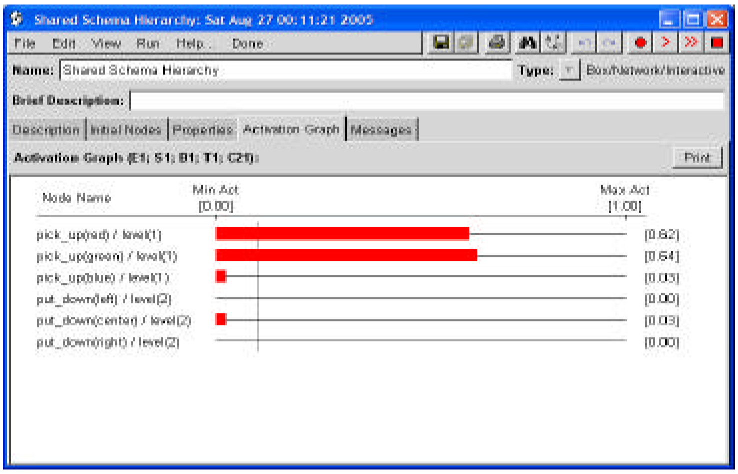
5.7 below. For example, in figure 5.4 above, either the red or green ball can be moved. Thus, excitatory messages are sent to Shard Schema Hierarchy that activate nodes for ‘pick up red’ and ‘pick up green’.

Excerpt 5.7 Excitation rules

```
Rule 2 (unrefracted): Rule
IF:     task(incomplete) is in Working Memory
        holds(hand, nothing) is in Current State
        ball_can_move(Ball)
THEN: send excite(pick_up(Ball) / level(1), 0.20) to Shared Schema Hierarchy

Rule 3 (unrefracted): If the hand's empty, excite pick up from any non-empty peg
IF:     task(incomplete) is in Working Memory
        holds(hand, nothing) is in Current State
        any_peg(Peg)
THEN: send inhibit(put_down(Peg) / level(2), 0.60) to Shared Schema Hierarchy

Condition Definition: any_peg/1: Names of pegs
any_peg(left)
any_peg(middle).
any_peg(right).

Rule 4 (unrefracted): Rule
IF:     holds(hand, Ball) is in Current State
        not holds(hand, nothing) is in Current State
        left_has_space
THEN: send excite(put_down(left) / level(2), 0.20) to Shared Schema Hierarchy

Rule 5 (unrefracted): Rule
IF:     holds(hand, Ball) is in Current State
        not holds(hand, nothing) is in Current State
        center_has_space
THEN: send excite(put_down(center) / level(2), 0.20) to Shared Schema Hierarchy

Rule 6 (unrefracted): Rule
IF:     holds(hand, Ball) is in Current State
        not holds(hand, nothing) is in Current State
        right_has_space
THEN: send excite(put_down(right) / level(2), 0.20) to Shared Schema Hierarchy
```

The accumulated levels of activation for the red and green balls are captured in the graph below (see Fig 5.8). Each node within a level competes for control of behaviour by inhibiting the other nodes. This process of **lateral inhibition** ensures only one node wins and thus only one action carried out.

Figure 5.8 The activation of schema nodes



Shared Schema Hierarchy: Sat Aug 27 00:11:21 2005

Name: Shared Schema Hierarchy **Type:** Box/Network/Interactive

Brief Description:

Activation Graph (E1; S1; B1; T1; C21):

Node Name	Min Act [0.00] … Max Act [1.00]
pick_up(red) / level(1)	[0.62]
pick_up(green) / level(1)	[0.64]
pick_up(blue) / level(1)	[0.03]
put_down(left) / level(2)	[0.00]
put_down(center) / level(2)	[0.03]
put_down(right) / level(2)	[0.00]

Once the threshold is reached and the selected action carried out, the contents of Current State and Working Memory is updated to reflect the new positions of balls and the process of determining the next possible move begins.

5.3.4 Model summary

The key features of the Simple CS model are (a) moves are performed at random, subject only to the physical constraints imposed by the ToL apparatus and (b) a process of lateral inhibition ensures only one action at a time is ever selected. A rule in Perception of World terminates processing and triggers the Experimenter to score performance on the task according to the four criterion measures. These data are presented below in Table 5.9 & 5.10 with the comparison data from the experimental study.

Table 5.9 Tower-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
Simple CS	499	100%	100.00	0.00

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	9.23	58.33	95.83	43.75
5-6 year olds	7.73	98.24	97.37	22.79

Table 5.10 Flat-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
Simple CS	308.47	100%	100.00	0.00

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	13.29	74.30	95.83	60.42
5-6 year olds	11.84	91.23	94.73	21.05

The assessment of this model is somewhat positive on two criterion measures. Namely, the model achieves 100% success for both configuration and the number of colours in place. This bears some resemblance to the performance of both experimental groups. However, the model fails to simulate either of the groups on the total number of moves made and the prevalence of rule breaks (i.e. many hundreds of moves were necessary to achieve the solution and the model did not pick-up with 'two-hands'). These failings suggest two modifications: (1) to introduce a strategy that organises behaviour more efficiently and (2) to reduce the influence of lateral inhibition.

5.4 Contention Scheduling 'plus' (CS+) model

The CS+ model embellishes on the Simple CS model by introducing a direct perceptual strategy and by reducing the influence of lateral inhibition within Shared Schema Hierarchy. The direct strategy implemented consists of a bias for organising problem-elements according to the *configural similarity* of the Current and Desired states and is aimed to reduce the total number of moves made.[14] Reducing lateral inhibition is aimed to allow more than one action schema (e.g., picking up two balls at a time) to occur.

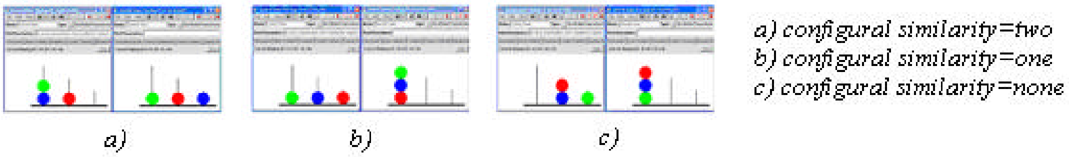
5.4.1 Organising behaviour

Configural similarity refers to the degree to which the Current and Desired States appear similar (see figure 5.11). In addition to maintaining representations of the environment in Working Memory, Perception of World functions to provide information that allows the level of configural similarity to be determined. In this way a number of possible action schemas can emerge that are based upon direct perceptual features.

---

[14] A 'hill-climb' strategy was also considered. This entails random moves of balls but allows a gradual progression towards the successful solution by leaving a ball once it has been correctly placed.

Fig 5.11 Configural similarity of three problems



a) configural similarity=two
b) configural similarity=one
c) configural similarity=none

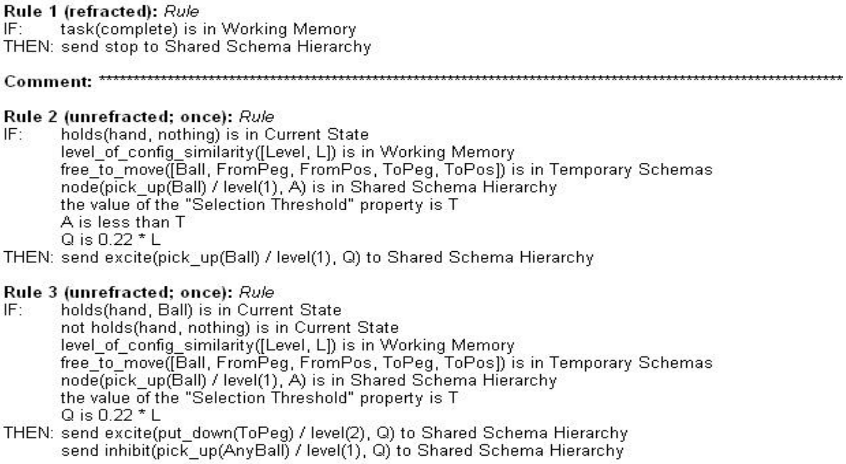
The first step the CS+ model takes is to identify the number of balls that are out of configural position. For each ball that is out of place, a schema is proposed to move it. E.g., in Figure 5.11.a above, the blue and red balls are in correct configural positions (only red in its actual colour position) but the green ball is out of place. Thus in this example, only one schema would be generated – to move the green to the left peg.[15]

The second step is in determining the amount of activation each schema should receive. In line with the hypothesis that the simple features of a given problem overly influence children it was considered that the amount of activation should be relative to the degree of perceptual similarity that exists at any one time. To achieve this, a baseline level of 0.22 was set to interact with the level of configural similarity. That is, if the level of configural similarity is high, the level of activation (or influence) to complete that particular configuration is also high. So, for instance based on Fig 5.11.a above, the schema to move the green to the left peg would produce an excitation of 0.66 within Shared Schema Hierarchy. Two rules in Trigger Schemas (rules 2 & 3 of excerpt 5.12 below) implement these steps.

Although fewer moves overall would have been made it would still require a great many to reach the desired state.

[15] In other circumstances, there may be as many as three possible schemas (no balls in correct configural position) or, no possible schemas (the Current and the Goal match in terms of their configurations) being offered.

Excerpt 5.12 Rules for exciting and inhibiting action schemas



Rule 1 (refracted): *Rule*
IF: task(complete) is in Working Memory
THEN: send stop to Shared Schema Hierarchy

Comment: **

Rule 2 (unrefracted; once): *Rule*
IF: holds(hand, nothing) is in Current State
level_of_config_similarity([Level, L]) is in Working Memory
free_to_move([Ball, FromPeg, FromPos, ToPeg, ToPos]) is in Temporary Schemas
node(pick_up(Ball) / level(1), A) is in Shared Schema Hierarchy
the value of the "Selection Threshold" property is T
A is less than T
Q is 0.22 * L
THEN: send excite(pick_up(Ball) / level(1), Q) to Shared Schema Hierarchy

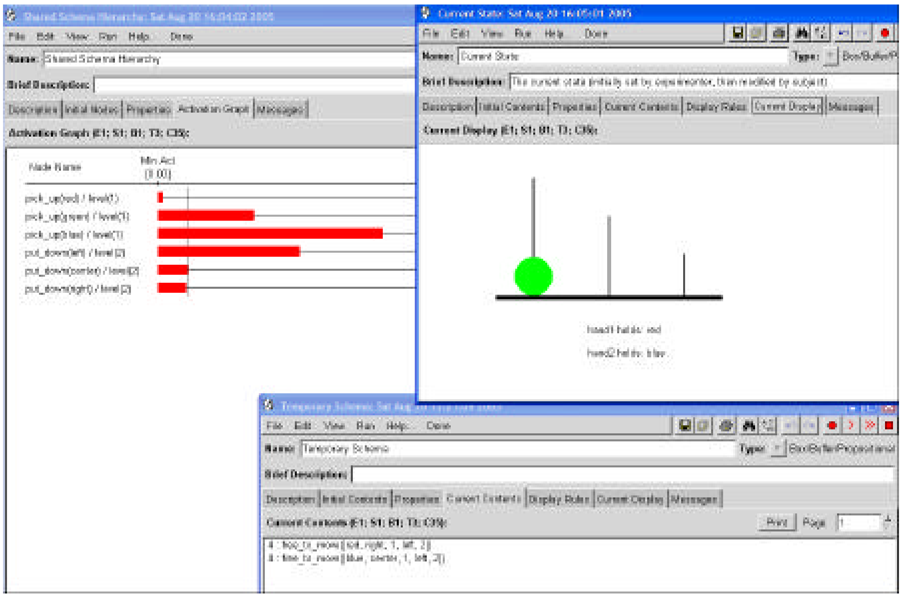
Rule 3 (unrefracted; once): *Rule*
IF: holds(hand, Ball) is in Current State
not holds(hand, nothing) is in Current State
level_of_config_similarity([Level, L]) is in Working Memory
free_to_move([Ball, FromPeg, FromPos, ToPeg, ToPos]) is in Temporary Schemas
node(pick_up(Ball) / level(1), A) is in Shared Schema Hierarchy
the value of the "Selection Threshold" property is T
Q is 0.22 * L
THEN: send excite(put_down(ToPeg) / level(2), Q) to Shared Schema Hierarchy
send inhibit(pick_up(AnyBall) / level(1), Q) to Shared Schema Hierarchy

5.4.2 Rule breaks

Lateral inhibition was reduced between competing nodes in Shared Schema Hierarchy. By changing this constraint the model was allowed to exhibit a common rule break performed by both experimental groups - namely, picking up two balls at a time.

The example below in Fig 5.13 (Task 3, a 5-move, tower-ending problem) illustrates one instance in which two possible moves are proposed and which results in this rule break.

Fig 5.13 Committing a rule break (holding two balls)



In the absence of strong lateral inhibition between nodes, the activation of both 'pick-up red' and 'pick-up blue' reach threshold and result in both actions being taken. The addition of the configural strategy results in both balls being placed on the left peg (the correct configuration, but only one correct colour position).

5.4.3 Model summary

The Simple CS model suggested two improvements: the introduction of an organising strategy and the reduction of lateral inhibition. These were implemented in this CS+ model and contributed to a greater fit with the experimental data on: (1) the number of correct configurations (2) the total number of moves made and (3) the appearance of rule-breaks (in the form of picking-up with two hands). These closely resembled data from the experimental groups (see table 5.14 & 5.15).

Table 5.14. Tower-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
CS+	7.58	26.79	98.03	58.82

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	9.23	58.33	95.83	43.75
5-6 year olds	7.73	98.24	97.37	22.79

Table 5.15 Flat-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
CS+	3.80	12.94	99.30	47.27

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	13.29	74.30	95.83	60.42
5-6 year olds	11.84	91.23	94.73	21.05

However, the model failed to simulate the data on the total number of colours in the correct position. This observation suggests the necessity for more complex strategies. These strategies should enable *planning* of moves of specific balls to specific locations.

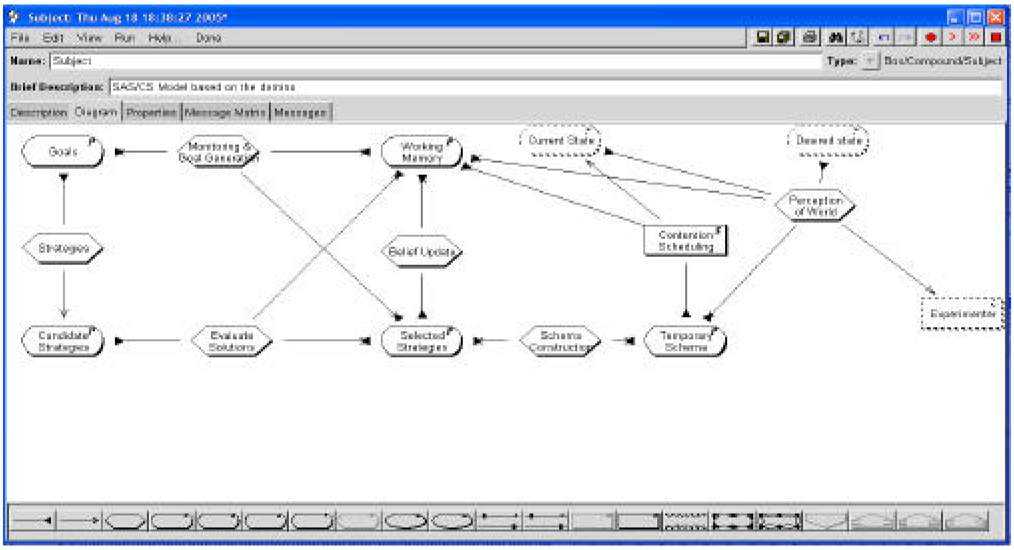
5.5 The 'Younger Child' model

The Younger Child model retains the structure and processes within the CS+ model and adds a distinct SAS/domino feel (see figure 3.3 above) in the role that the processes and buffers take. Based on the previous model's failings and derived from research (see above), the two additional strategies: *immediate-hits* and *one-move look-ahead*, are implemented. It is intended these will enable the planning of moves of balls to their target locations.

5.5.1 *The Subject: introducing supervisory components*

Figure 5.16 shows the processes within Subject. CS on the right hand side is carried over from the previous model and a number of new processes are added. **Perception of World** offers representations of the Current and Desired states to Working Memory. The left-hand side of the model is given over to 'decision-making' as strategies are generated and analysed by **Evaluate Solutions**. For each Selected Strategy action schemas are created (via **Schema Construction**) and fed into **Temporary Schemas**, serving to excite elements within Contention Scheduling.

Figure 5.16 The Subject level illustrating a generalised domino approach



Name: Subject

Type: Box/Compound/Subject

Brief Description: SAS/CS Model based on the domino

5.5.2 Monitoring and Goal Generation

Problems are recognised as problems by **Monitoring and Goal Generation** (Monitoring), if the Current and Desired states do not exactly match. When there is a discrepancy between these two states, a message is produced and sent to **Goals** that triggers the production of two strategies aimed at reducing the difference.

5.5.3 Strategies

The immediate-hits strategy translates to: the immediate placement of a ball at its target position, if (a) it is free to move and (b) its target position is free. The one-move look-ahead strategy is slightly more complex and corresponds to: the ability to evaluate the resultant state of a possible move (i.e., is one move ahead). These strategies are produced by **Strategies** and sent as **Candidate Strategies** where they are fed into Evaluate Solutions.

5.5.4 Evaluate Solutions

Evaluate Solutions provides intensive processing of information represented within Working Memory and to a lesser extent Selected Strategies. As its name implies, the primary objective for this process is to evaluate the outcome of proposed solutions, or moves.

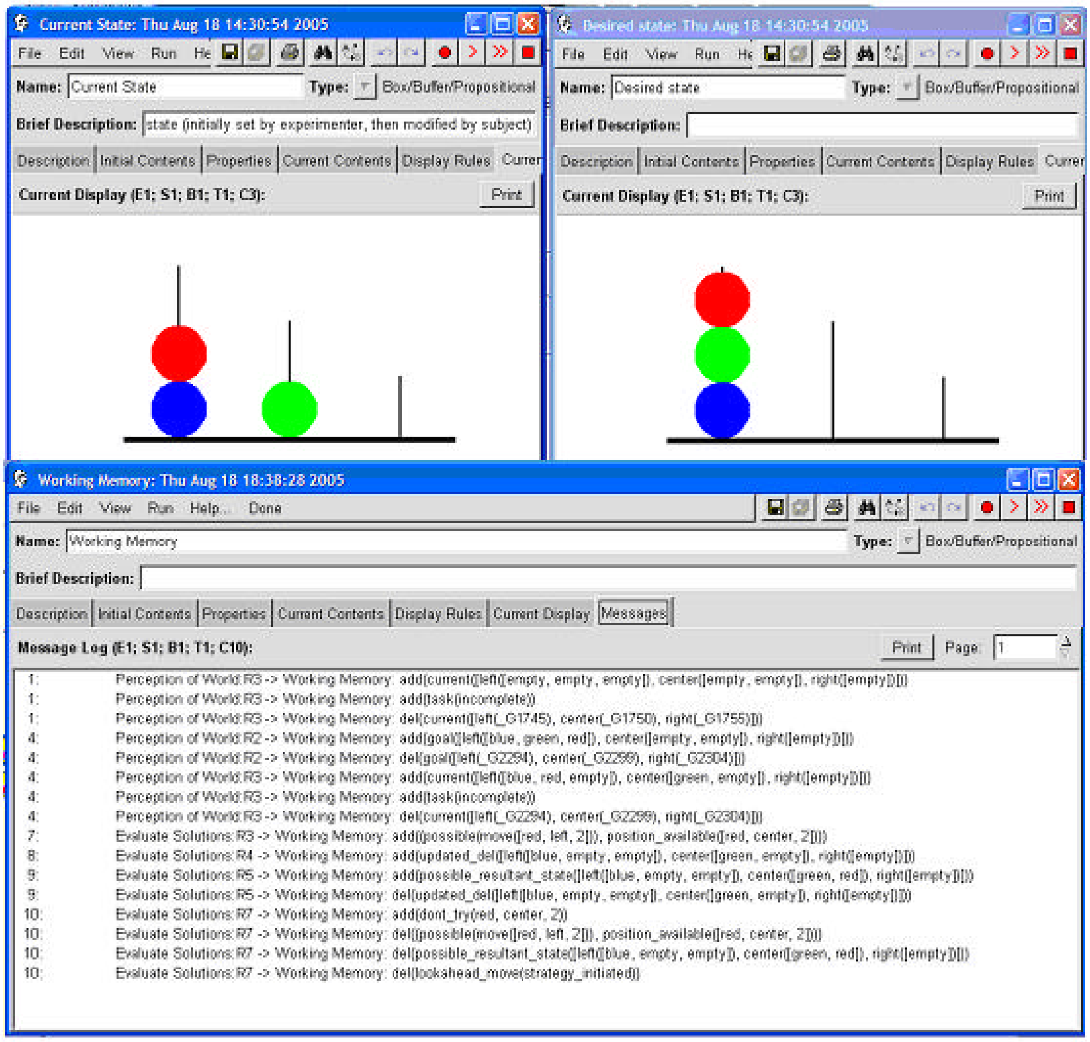
Evaluate Solutions is responsible for identifying immediate-hits. In the event where none exist Evaluate Solutions starts a process whereby possible moves are proposed to Working Memory. Evaluate Solutions calculates what the *resultant state* would be if that possible move was actioned. If an immediate-hit is possible given a resultant state the possible move is initiated.[16] For instance, in figure 5.17 below, one possible move (move red to right peg) would lead to a resultant state where an immediate hit (green to left peg) would be possible. This would represent a successful implementation of the one-move look-ahead strategy.

---

[16] This tendency to abandon full searches of the problem space for other beneficial moves is consistent with the literature (Gilhooly, 2002).

If a possible move does not yield an outcome whereby an immediate hit is possible then it is temporarily 'black listed' in working memory and the next possible resultant state is evaluated. This process can be seen in the message log of Working Memory, (figure 5.17).

Figure 5.17 A log of the actions on Working Memory



Current State: Thu Aug 18 14:30:54 2005

Name: Current State **Type:** Box/Buffer/Propositional

Brief Description: state (initially set by experimenter, then modified by subject)

Current Display (E1; S1; B1; T1; C3):

Desired state: Thu Aug 18 14:30:54 2005

Name: Desired state **Type:** Box/Buffer/Propositional

Brief Description:

Current Display (E1; S1; B1; T1; C3):

Working Memory: Thu Aug 18 18:38:28 2005

Name: Working Memory **Type:** Box/Buffer/Propositional

Brief Description:

Message Log (E1; S1; B1; T1; C10): Page: 1

```
 1:   Perception of World:R3 -> Working Memory: add(current([left([empty, empty, empty]), center([empty, empty]), right([empty])]))
 1:   Perception of World:R3 -> Working Memory: add(task(incomplete))
 1:   Perception of World:R3 -> Working Memory: del(current([left(_G1745), center(_G1750), right(_G1755)]))
 4:   Perception of World:R2 -> Working Memory: add(goal([left([blue, green, red]), center([empty, empty]), right([empty])]))
 4:   Perception of World:R2 -> Working Memory: del(goal([left(_G2294), center(_G2299), right(_G2304)]))
 4:   Perception of World:R3 -> Working Memory: add(current([left([blue, red, empty]), center([green, empty]), right([empty])]))
 4:   Perception of World:R3 -> Working Memory: add(task(incomplete))
 4:   Perception of World:R3 -> Working Memory: del(current([left(_G2294), center(_G2299), right(_G2304)]))
 7:   Evaluate Solutions:R3 -> Working Memory: add([possible(move([red, left, 2])), position_available([red, center, 2])])
 8:   Evaluate Solutions:R4 -> Working Memory: add(updated_del([left([blue, empty, empty]), center([green, empty]), right([empty])]))
 9:   Evaluate Solutions:R5 -> Working Memory: add(possible_resultant_state([left([blue, empty, empty]), center([green, red]), right([empty])]))
 9:   Evaluate Solutions:R5 -> Working Memory: del(updated_del([left([blue, empty, empty]), center([green, empty]), right([empty])]))
10:   Evaluate Solutions:R7 -> Working Memory: add(dont_try(red, center, 2))
10:   Evaluate Solutions:R7 -> Working Memory: del([possible(move([red, left, 2])), position_available([red, center, 2])])
10:   Evaluate Solutions:R7 -> Working Memory: del(possible_resultant_state([left([blue, empty, empty]), center([green, red]), right([empty])]))
10:   Evaluate Solutions:R7 -> Working Memory: del(lookahead_move(strategy_initiated))
```

Messages 1-4 correspond to changes in Working Memory contents as the task is set up. In message 7: a possible move of Red to the centre peg, position 2 is proposed. Message 9a returns a representation of what the resultant state would be. Because Evaluate Solutions does not then find this to produce the possibility of an Immediate Hit, message 10a (of the form, "don't try red to centre peg") is sent to Working Memory.

5.5.5 Schema Construction

Schema Construction performs a limited but essential role in this model. Last in the decision-making chain, it creates and adds new temporary schemas on the basis of results from Selected Strategies that are then fed into the CS system. It also acts to remove old schemas from Temporary Schemas thus improving the chance that only relevant schemas remain to influence action.

5.5.6 Belief Update

Belief Update serves to action results from Evaluate Strategies by modifying the contents of Working Memory so that only task-relevant information is included. Specifically, if a strategy has been adopted (e.g., to begin a one-move look-ahead), then Working Memory is cleared of information relating to other possible moves.

5.5.7 Model summary

The need for strategic planning in increasing the numbers of colours that are placed in their correct positions was implemented in this model in the form of (1) an immediate-hits strategy and (2) a one-move look-ahead strategy. These supervisory strategies were combined with the bias for configural similarity examined in CS+ model and influences of both systems were found on performance.

Assessment of this model reveals a reasonable fit for the data of the 3-4 year olds on all of the criterion measurements (see table 5.18 & 5.19). However, the model fails to simulate the 5-6 year olds on number of colours in correct position. One explanation for this is that whilst the adoption of strategies within this model increased the proportion of colours in correct positions the more direct the influence of CS went unchecked. That is, the two systems are not co-ordinated in their efforts. For example, in the course of a task the perceptual features of a problem are present *before* the results of processing of the various strategies have been carried out. The CS (containing the bias for configural similarity) is dependant on perceptual information only and thus has an early advantage at influencing the selection of schemas.

Table 5.18 Tower-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3) Younger Child	6.70	65.74	95.00	64.70

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	9.23	58.33	95.83	43.75
5-6 year olds	7.73	98.24	97.37	22.79

Table 5.19 Flat-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3) Younger Child	6.90	65.74	96.07	23.52

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	13.29	74.30	95.83	60.42
5-6 year olds	11.84	91.23	94.73	21.05

The lack of co-ordination between CS and supervisory processes suggests the need for greater monitoring and control to *inhibit* the influence of simple and direct perceptual biases that originate from the CS+ side of the model. Introducing a mechanism that achieves this may thus account for the differences between age groups.

5.6 The 'Older Child' model

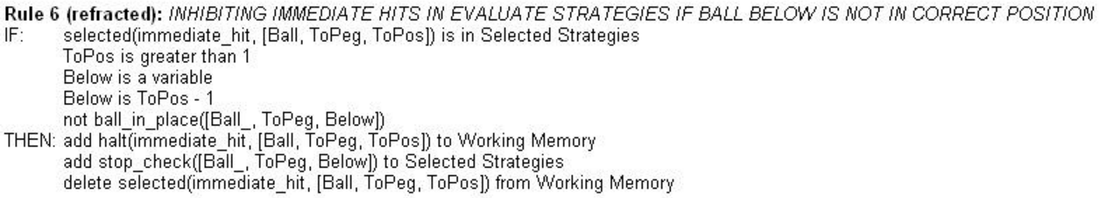
Using the Younger Child model as the initial platform, this model extends upon the previous model by prioritising higher-level strategies over those lower-level strategies offered by CS. Thus, it aims to achieve correct configuration and correct colour positions on the range of tasks offered on the ToL by inhibiting the influence of direct perceptual biases.

5.6.1 Inhibition of immediate moves

In a strong top-down manner, Monitoring and Goal Generation intervenes directly in the process of PS by temporarily suppressing a move if the position to which the ball is to be placed is *above* another ball. Thus, either moves that are triggered by a configural bias (within CS), or moves that are proposed by the immediate-hit strategy (via Evaluate Solutions) are halted until further checks are carried out.

This difference between the Younger Child model and Older Child model is embodied within a single rule in Monitoring and Goal Generation. This rule, (see excerpt 5.20 below) triggers a more detailed examination of the positions of other balls in the current state if an immediate-hit has been triggered. If a ball under the target position for the immediate-hit is not in place, the strategy is terminated and a new move considered.

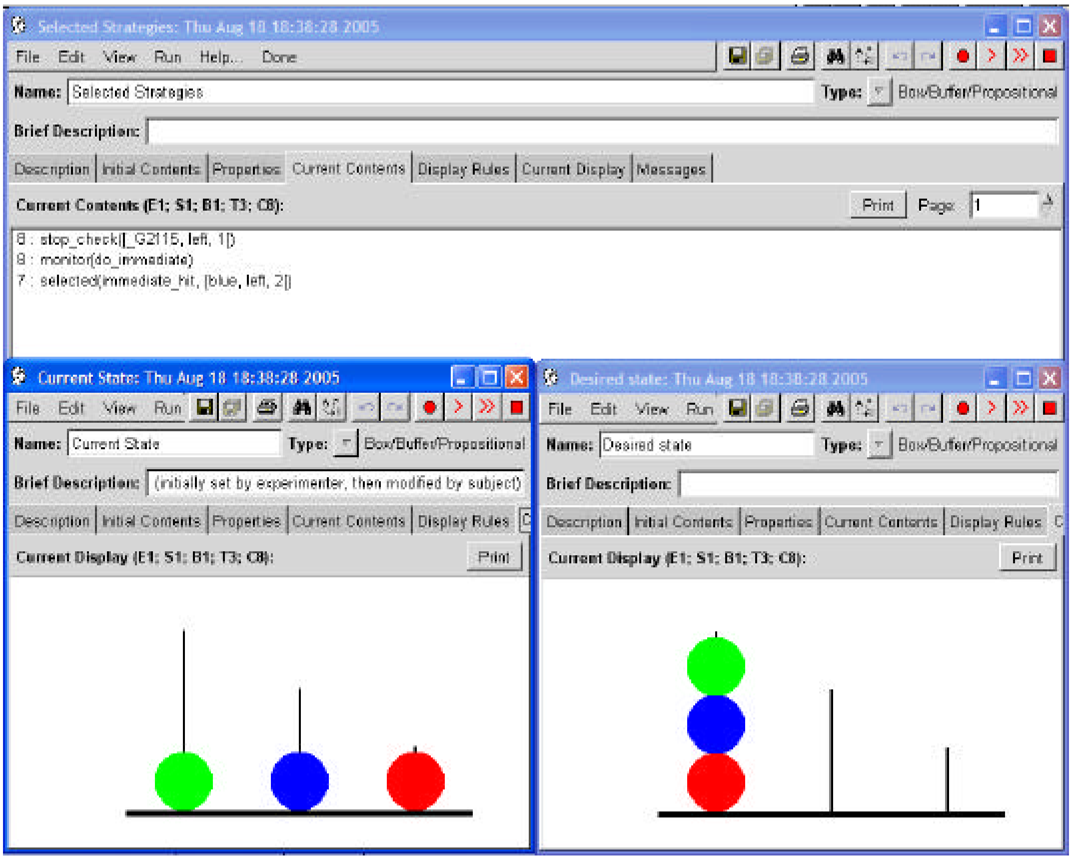
Excerpt 5.20 Inhibiting immediate-hit if ball under is not in place



```
Rule 6 (refracted): INHIBITING IMMEDIATE HITS IN EVALUATE STRATEGIES IF BALL BELOW IS NOT IN CORRECT POSITION
IF:     selected(immediate_hit, [Ball, ToPeg, ToPos]) is in Selected Strategies
        ToPos is greater than 1
        Below is a variable
        Below is ToPos - 1
        not ball_in_place([Ball_, ToPeg, Below])
THEN:   add halt(immediate_hit, [Ball, ToPeg, ToPos]) to Working Memory
        add stop_check([Ball_, ToPeg, Below]) to Selected Strategies
        delete selected(immediate_hit, [Ball, ToPeg, ToPos]) from Working Memory
```

This rule can be seen operating in figure 5.21 below. Message 7 in Selected Strategies (top section) shows an immediate-hit for blue to the left peg is proposed. The Current State (pictured bottom-left) shows this to be the correct position for blue, but would result in green under being blocked. Message 8, halts the application of an immediate-hit via rule 6 above.

Fig 5.21Illustration of inhibition of immediate move



Name: Selected Strategies **Type:** Box/Buffer/Propositional

Brief Description:

Current Contents (E1; S1; B1; T3; C8): Page: 1

```
8 : stop_check([_G2115, left, 1])
8 : monitor(do_immediate)
7 : selected(immediate_hit, [blue, left, 2])
```

Name: Current State **Type:** Box/Buffer/Propositional

Brief Description: (initially set by experimenter, then modified by subject)

Current Display (E1; S1; B1; T3; C8):

Name: Desired state **Type:** Box/Buffer/Propositional

Brief Description:

Current Display (E1; S1; B1; T3; C8):

In the example above, the immediate-hit strategy is aborted because the move (blue to left peg) would result in green being blocked.

5.6.2 *Model summary*

Using the Younger Child model as a platform this final model adds an important feature that serves to inhibit actions that are based on simple and direct perceptual biases. These biases are suppressed via a rule that triggers a deeper search of the problem state. Crucially, this mechanism works by performing checks *before* allowing schema nodes to be influenced.

The effects of this mechanism within the Monitoring process is in reducing the chances of the model being ‘led astray’ by superficial characteristics of the problem and increasing the proportion of balls being placed in their correct colour position.

Table 5.22 & 5.23 reveals a good level of overall fit on the criterion measures of this model to the data from the 5-6 year olds

Table 5.22 Tower-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
4) Older Child	6.45	95.43	98.00	28.22

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	9.23	58.33	95.83	43.75
5-6 year olds	7.73	98.24	97.37	22.79

Table 5.23 Flat-ending problems collapsed across task difficulty.

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
4) Older Child	7.88	94.67	97.67	32.71

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	13.29	74.30	95.83	60.42
5-6 year olds	11.84	91.23	94.73	21.05

5.7 Main summary of results

At a general level, the series of model demonstrate a move towards a functional system that simulates the behaviour of children on ToL tasks (see figures 5.24 & 5.25). The first two models each demonstrated the necessity for the involvement of strategic planning in PS on the ToL. Though the transition from the first to the second model offered a better simulation of rule breaks for both groups the numbers of balls in place were considerably fewer than in either of the experimental groups. The third model offered a better simulation of the 3-4 year olds and exhibits a mixture of influences from (1) direct perceptual biases and (2) strategic planning on performance that indicated the need to suppress perceptual biases. In the final model, inhibition of these biases is considered key in accounting for greatly improved performance and the good fit with the data from the 5-6 year olds.

Table 5.24 Summary of computational models and the experimental data (tower-ending problems collapsed across task difficulty).

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
1) Simple CS	499	100.00	100.00	0.00
2) CS+	7.58	26.79	98.03	58.82
3) Younger Child	6.70	65.74	95.00	64.70
4) Older Child	6.45	95.43	98.00	28.22

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	9.23	58.33	95.83	43.75
5-6 year olds	7.73	98.24	97.37	22.79

Table 5.25 Summary of computational models and the experimental data (flat-ending problems collapsed across task difficulty).

Computational models

Model	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
1) Simple CS	308.47	100.00	100.00	0.00
2) CS+	3.80	12.94	99.30	47.27
3) Younger Child	6.90	65.74	96.07	23.52
4) Older Child	7.88	94.67	97.67	32.71

Experimental data

Children	Avg. no. moves	Total proportion colours in correct place	Total no. correct configuration	Total proportion rule breaks
3-4 year olds	13.29	74.30	95.83	60.42
5-6 year olds	11.84	91.23	94.73	21.05

With regard to differences on tower vs. flat-ending problems, these models show no clear dissociation of performance. That is, their performance is noticeably stable on either of the two problem types. For example, the 3-4 year olds appear to do better at matching colours on flat-ending tasks than on tower-ending tasks but in the process also commit a greater number of rule breaks. The Younger Child model does not capture this subtle pattern of behaviour.

Overall, from this data it may appear inhibition holds a considerable influence on the overall behaviour of the Older Child model. However, the final outcome on each task is reliant on a number of other processes. These interpretations fit well both with diversity accounts and studies emphasising a strong involvement of inhibition on tasks of EF, including the ToL (Miyake et al, 2000).

6 General discussion

The series of models presented here form an attempt to integrate a number of aspects from related fields interested in the process of problem solving. In the final Older Child model one view of the possible role that inhibition may play in PS on the ToL was established. This view was built on a platform from which conceptualisations of EF mechanisms (offered by Miyake et al, 2000) were combined with generalised frameworks of decision-making and problem solving (Norman & Shallice, 1986; and Fox & Das, 2000). The effects of these influences on the final two models can be seen in a number of key ways.

Firstly, effects may be seen at a structural level. Here, the Younger Child and Older Child models share characteristics common to both the CS-SAS and the domino with a number of direct one-to-one mappings being observable (see Glasspool, 2005).

Secondly, these models strongly favour diversity views of EF in the way component processes interact in the process of PS. That is, behaviour is not guided through any one single mechanism, but rather is the outcome of a range of processes. Although it is argued a specific role given to inhibition is instrumental in accounting for differences between the Younger Child and Older Child models, performance overall is a result of a number of influences.

The work presented here argues the case that younger children's poorer performance on the ToL is a product of their failure to inhibit simpler strategies. Furthermore, these models are taken to suggest that in contrast to the view that younger and older children possess qualitatively different cognitive strategies, the lack of ability to inhibit may mask the existence of more complex skills.

Work on the latter two models is not finished. There are a number of issues that would benefit from further investigation that may be divided into a) practical issues and b) conceptual issues.

At the practical level, an important issue that these models do not attempt in their functioning is the ability to *backtrack*. As children mature and proficiency on PS increases, the ability to make counter-intuitive moves (moves that appear to take the current away from the goal state) appears. Backtracking was observed on very few occasions by the 5-6 year olds, though this suggests the ability is perhaps only just emerging at these ages. Combining this within an account of PS would provide a fuller model of behaviour and possibly highlight better the role of inhibition. For instance, it is likely that backtracking could be implemented by inhibiting simpler strategies. This is something future work could investigate.

A second issue of practicality relates to the actual tasks used. Analysis of each of the tasks administered in the original study (and replicated here) revealed the solutions were all possible given a combination of immediate-hits and one-move look-ahead strategies. In order to further tease apart the kinds of strategies that may exist in young children, a broader range of tasks should be administered. These should include problems requiring a look-ahead of two, three and four-moves. As problem difficulty increases in this way, one might expect an increasing reliance on simple perceptual strategies and a reduction in overall correct colours by younger children. Thus, one question raised is: What role does inhibition play in later PS ability? And, if the capacity for greater look-ahead moves increases with age, what function does inhibition serve? It seems likely that the role outlined within these models would be insufficient in accounting for this behaviour.

At the conceptual level, it is considered that this paper allows for a description of the process of PS in young children that fits with a number of views. The models are not considered to contribute to questions on the *development* of mechanisms underlying PS processes and no attempt is made to provide description of how, for example, inhibition may emerge in the Older Child model. However, as discussed earlier, links between the development of frontal lobes and abilities on PS tasks provide some degree of consistency between these models and existing developmental literature (though see, Happaney, 2004).

Lastly, one important criticism that might be raised relates to the problem of *functional equivalence*. That is, different implementations of the same process that function in very different ways may produce equivalent behavioural outcomes. In this paper the Younger Child and Older Child model were identical with the exception of a single rule that operated to inhibit certain types of actions. But, it is possible that the same set of data could be produced, by manipulation of some other variable(s). For example, in the representations the two models receive (e.g., Gertner, Ratterman, Markmann & Kotovsky, 1995). Critical assessment of the rationale underlying each alternative implementation is thus considered key in disentangling questions of functional equivalence.

Getting away from problems posed by functional equivalence, is hoped will be facilitated in part by greater converging evidence from a range of disciplines and the use of a range of tools. As evidence gathers within these other fields and more sensitive measurements and descriptions are sought, the nature and interaction of mechanisms underlying EF and behaviour in general, is hoped will become clearer.

References

Altmann, E. M. & Gray, W. D. (1999). Serial Attention as Strategic Memory. *Proceedings of the twenty first annual meeting of the Cognitive Science Society*, 1–7. Hillsdale, NJ: Erlbaum.

Altmann, E. M. & Trafton, J. G. (1999). Memory for Goals: An Architectural Perspective. *Proceedings of the twenty first annual meeting of the Cognitive Science Society,* 19–24. Hillsdale, NJ: Erlbaum.

Anderson, V. (1998). Assessing executive functions in children: Biological, psychological, and developmental considerations. *Neuropsychological Rehabilitation, 8,* 319–349.

Anderson, J.R. (1983*). The architecture of cognition*. Harvard: Harvard University Press.

Anderson, J. R., & Lebiere, C. (1998*). Atomic Components of Thought.* Maywah, NJ: Erlbaum.

Baker, S. C., Rogers, R. D, Owen, A. M, Frith, C. D, Dolan, R. J., Frackowiak, R. S. J., & Robbins, T. W. (1996). Neural systems engaged by planning: a PET study of the Tower of London task. *Neuropsychologia, 34,* 515–526.

Bull, R., Espy, K. A., & Senn, T. E. (2004). A Comparison of Performance on the Towers of London and Hanoi in Young Children. *Journal of Child Psychology and Psychiatry 45:4*, 743–754.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology, 19,* 273–293.

Carpenter, P. A., Just, M. A., & Reichle, E. D. (2000). Working memory and executive function: evidence from neuroimaging. *Current Opinion in Neurobiology, 10,* 195–199.

Charman, T., Carroll, F., & Sturge, C. (2001). Theory of mind, executive functions and social competence in boys with ADHD. *Emotional and Behavioral difficulties, 6(1),* 31–49.

Cohen, G., & O'Leary, D. S. (1992). Hypofrontality in neuroleptic-naïve patients and in patients with chronic schizophrenia: assessment with Xenon 113 single-photon emission computed tomography and the Tower of London. *Arch Gen Psychiatry, 49,* 943–958.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97,* 332–361.

Cooper, R.P. and Shallice, T. (1995). Soar and the case for Unified Theories of Cognition. *Cognition, 55,* 115–149.

Cooper, R.P. & Fox, J. (1998). COGENT: A visual design environment for cognitive modelling. *Behaviour Research Methods, Instruments, & Computers, 30,* 553–564.

Cooper, R.P. (2002). *Modelling High-Level Cognitive Processes*. Lawrence Erlbaum Associates, Mahwah, NJ.

Damasio, A. R. (1994). *Descartes' error: Emotion, reason, and human brain*. New York: Grosset/Putnam

Diamond, A., Kirkham, N., & Amso, D. (2002). Conditions Under Which Young Children Can Hold Two Rules in Mind and Inhibit a Prepotent Response. *Developmental Psychology, 38,* 3, 352–362.

Ernst, G. W., & Newell, A. (1969). *GPS: A case study in generality in problem solving*. New York: Academic Press.

Espy, K. A., Kaufmann, P. M., McDiarmid, M. D., & Glisky, M. L. (1999). Executive functioning in preschool children: Performance on A-not-B and other delayed response format tasks. *Brain and Cognition, 41*, 178–199.

Fodor, J. A., & Pylyshyn, Z. W. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition,* 28, 3–71.

Fox J. (2005*)*. Images of Mind: In Memory of Donald Broadbent and Allen Newell. In D. N. Davis (Ed.) *Visions of Mind: Architectures for Cognition and Affect* (pp. 125–148). Hershey, PA: IDEA Group.

Fox, J. & Das, S. (2000). *Safe and Sound: Artificial Intelligence in Hazardous Applications*. MIT press, Cambridge, MA.

Gazzaniga, M. S., Ivry, R., & Mangun, G. R. (2002). *Cognitive Neuroscience: The Biology of the Mind.* Norton. 2nd Ed.

Gentner, D., Rattermann, M., Markman, A., & Kotovsky, L. (1995). Two forces in the development of relational similarity. In T. J. Simon & G. S. Halford (Eds.), *Developing cognitive competence: New approaches to process modeling* (pp. 263–313). Hillsdale, NJ: Erlbaum.

Gilhooly, K. J. (2002). *Thinking: Directed, Undirected and Creative*. Academic Press.

Glasspool D.W. (2005). The integration and control of behaviour: Insights from neuroscience and AI. In D. N. Davis (Ed.) *Visions of Mind: Architectures for Cognition and Affect* (pp. 208–234). Hershey, PA: IDEA Group.

Glasspool, D.W. & Cooper, R.P. (2002). Executive Processes. In Cooper, R.P. (ed.) *Modelling High-Level Cognitive Processes* (pp. 313–362). Lawrence Erlbaum Associates, Mahwah, NJ.

Goel, V., Pullara, S. D., & Grafman, J. (2001). A computational model of frontal lobe dysfunction: Working memory and the Tower of Hanoi task. *Cognitive Sciences, 25,* 287–313.

Goldman-Rakic, P. S. (1987). Development of cortical circuitry and cognitive function. *Child Development, 58,* 601–622.

Gratch, G. (1975). Recent studies of Piaget's view of object concept development. In Cohen, L. B., & Salapatek, P. (eds.), *Infant perception: From sensation to cognition,* (pp. 51–102). Academic Press, New York, NY.

Griffith, E. M., Pennington, B. F., Wehner, E. A., & Rogers, S. J. (1999). Executive functions in young children with autism. *Child Development, 70,* 817–832.

Gunzelmann, G., & Anderson, J. R. (2003). Problem solving: Increased planning with practice. *Cognitive Systems Research, 4*, 57–76.

Happaney, K., Zelazo, P. D., & Stussa, D. T. (2004). Development of orbitofrontal function: Current themes and future directions. *Brain and Cognition 55,* 1–10.

Harris, E. L., Schuerholz, L. J., Singer, H. S., Reader, M. J., Brown, J. E., Cox, C., Mohr, J., Chase, G. A., & Denckla, M. B. (1995). Executive function in children with Tourette Syndrome and/or Attention Deficit Hyperactivity Disorder. *Journal of the International Neuropsychological Society, 1,* 511–516.

Harvey, P. O., Le Bastard, G., Pochon, J. B., Levy, R., Allilaire, J. F., Dubois, B., & Fossati, P. (2004). Executive functions and updating of the contents of working memory in unipolar depression. *Journal of Psychiatric Research 38,* 567–576.

Hill, E. L. (2004). Evaluating the theory of executive dysfunction in autism. *Developmental Review, 24,* 189–233.

Houghton, S., Douglas, G., West, J., Whiting, K., Wall, M., Langsford, S., et al. (1999). Differential patterns of executive function in children with attention-deficit hyperactivity disorder according to gender and subtype. *Journal of Child Neurology, 14,* 801–805.

Hughes, C. (1998). Finding your marbles: Does preschoolers’ strategic behavior predict later understanding of mind? *Developmental Psychology, 34*, 1326–1339.

Hughes, C. and Graham, A. (2002). Measuring executive functions in childhood: problems and solutions? *Child and Adolescent Mental Health, 7,* 131–142.

Klahr, D. (1985). Solving problems with ambiguous subgoal order: preschoolers' performance. *Child Development, 56,* 940–952.

Klahr, D., & Robinson, M. (1981). Formal assessment of problem solving and planning processes in preschool children. *Cognitive Psychology, 13*, 113–148.

Klahr, D., & Wallace, J. G. (1976). *Cognitive development: An information processing view*. Hillsdale, NJ : Lawrence Erlbaum Associates .

Krikorian, R., Barton J., & Gay, N. (1994). Tower of London procedure: A standard method and developmental data. *Journal of Clinical and Experimental Neuropsychology, 16,* 840–850.

Kotovsky, K., Hayes, J. R., & Simon, H. A. (1985). Why are some problems hard? *Cognitive Psychology, 17,* 248–294.

Koziol, L. F., & Stout, C. E. (1992). Use of a verbal fluency measure in understanding and evaluating ADHD as an executive function disorder. *Perceptual and Motor Skills, 75,* 1187–1192.

Laird, J.E., Newell, A., Rosenbloom, P.S. (1987). "SOAR: An Architecture for General Intelligence". *Artificial Intelligence, 33,* 1–64.

Lehto, J. E., Juujarvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology, 21,* 59–80

Levine, D. S. (2000). *Introduction to Neural and Cognitive Modeling*. Mahwah, NJ: Lawrence Erlbaum Associates, 2nd Ed.

McClelland J. L. (1995) A connectionist perspective on knowledge and development. In: T. J. Simon and G. S. Halford (Eds) *Developing cognitive competence: New approaches to process modeling* (pp. 278–304). Hillsdale, NJ: Erlbaum.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100.

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

Mundy, P. (2003). The neural basis of social impairments in autism: The role of the dorsal medial-frontal cortex and anterior cingulated system. *Journal of Child Psychology and Psychiatry, 44,* 793–809.

Newell, A. (1990). *Unified Theories of Cognition*. Cambridge MA.: Harvard University Press.

Newell, A., & Simon, H.A. (1972*). Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.

Norman, D.A., & Shallice, T. (1986). Attention to action: willed and automatic control of behaviour. In R. Davidson, G. Schwartz, & D. Shapiro (Eds.), *Consciousness and self regulation* (Vol. 4). Plenum: New York.

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

Ozonoff, S & Jensen, J. (1999). Brief Report: Specific Executive Function Profiles in Three Neurodevelopmental Disorders. *Journal of Autism and Developmental Disorders, 29,* 2, 171–177

Phillips, L. H. (1997). Do ‘‘frontal tests’’ measure executive function? Issues of assessment and evidence from fluency tests. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 191–213). Hove, UK: Psychology Press.

Phillips, L. H., Wynn, V., Gilhooly, K. J., Della Sala, S., & Logie, R. H. (1999). The role of memory in the Tower of London task. *Memory, 7*, 209–231.

Plaut, D. C. & Shallice, T. (1993). Deep dyslexia: A case study of connectionist neuropsychology. *Cognitive Neuropsychology, 10,* 377–500.

Rabbitt, P. (1997). *Methodology of frontal and executive function*. Hove, UK: Psychology Press.

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

Reitan, R. M., & Wolfson, D. (1994). A selective and critical review of neuropsychological deficits and the frontal lobes. *Neuropsychology Review, 4*, 161–197.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124,* 207–231.

Rumelhart, D. E. (1989). The architecture of mind: A connectionist approach. In Posner. *Foundations of Cognitive Science*. Cambridge, MA: MIT Press.

Russell, J. (1999). Cognitive development as an executive process—in part: A homeopathic dose of Piaget. *Developmental Science, 2,* 247–295.

Schneider, W. & Shiffrin, R.M. (1977). Controlled and automatic processing: I. Detection, search and attention. *Psychological Review, 84,* 1–66.

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

Shallice, T., & Burgess, P. W. (1991). Deficits in strategy application following frontal lobe damage in man. *Brain, 114,* 727–741.

Simen, P., Polk, T., Lewis, R., & Freedman, E. (2004). A computational account of latency impairments in problem solving by Parkinson's patients. *In Proceedings of* *the Sixth International Conference on Cognitive Modeling*, 273–278, Mahwah,NJ: Lawrence Earlbaum.

Simon, H.A. (1975). The functional equivalence of problem solving skills. *Cognitive Psychology, 7,* 268–288.

Shultz, T., R. (2003). Computational explorations of cognitive development. *Proceedings of the Twenty-fifth Annual Conference of the Cognitive Science Society*. Mahwah, NJ: Erlbaum.

Sylvester, C.-Y. C., Wager, T. D., Lacey, S. C., Hernandez, L., Nichols, T. E., Smith, E. E., & Jonides, J. (2003). Switching attention and resolving interferences: fMRI measures of executive functions. *Neuropsychologia, 41*, 357–370.

Teuber, H.-L. (1972). Unity and diversity of frontal lobe functions. Acta *Neurobiologiae Experimentalis, 32*, 615–656.

Thomas, M. S. C., Mareschal, D., & Hinds, A. (2001). A connectionist account of the emergence of the literal-metaphorical-anomalous distinction in young children. *Proceedings of the 23rd Annual Meeting of the Cognitive Science Society*. Erlbaum.

Waldau, R. (1999). A developmental study of problem solving in children aged 3–6: Development of planning strategies. *Unpublished undergraduate dissertation. Department of Psychology, Birkbeck College, University of London.*

Welsh, M. C., & Pennington, B. F. (1988). Assessing frontal lobe functioning in children: Views from developmental psychology. *Developmental Neuropsychology, 4,* 199–230.

Zelazo, P. D., Carter, A., Reznick, J. S., & Frye, D. (1997). Early development of executive function: A problem-solving framework. *Review of General Psychology, 1, 198–226.*

Appendix 1: Summary of Waldau's (1999) study

The experimental data were obtained by consent from a previous study by Rikke Waldau (see, Waldau, 1999).

Design

The experiment followed a mixed design, with the between-subjects variable being age (3-4 yr olds and 5-6 yr olds) and the within-subjects variables being the level of difficulty (3,4, or 5 moves) and target configuration (tower vs. flat).

Participants

Seventeen 3-4 year olds and seventeen 5-6 year olds from a selection of inner-London nurseries took part in the study. Participants colour vision was assessed directly before the starting the training task.

Materials and apparatus

Six colour photographs of each of the goal states were used to illustrate the appropriate end-state. The TOL apparatus was made according to standardised specifications (see Krikorian, et al., 1994).

Procedure

Presentation of each set of six problems were randomised and counter balanced for participants. For each task, the experimenter began by setting up the problem by placing the balls in their initial positions. The following rules were explained to the child:

- Only one ball could be picked up at a time, and
- It had to be placed directly on to a peg (i.e., not placed on the table, or kept in the hand)

Then the child was shown the desired, or goal state and was free to start. In the training stage participants completed four TOL problems to a criterion level. Subjects were then required to solve six critical problems. Their performance was videotaped for later scoring. The familiarisation problems were all two and three move problems involving non-tower/non-flat goal configurations.

Following the training state, participants were given the actual task problems consisting of one three-move, one four-move, and one five-move tower-ending problem, and one three-move, one four-move, and one five-move flat-ending problem.

The problems were designed such that the same start configuration was used for tower-ending and flat-ending problems requiring the same number of moves. The order of presentation of critical tasks was randomised.

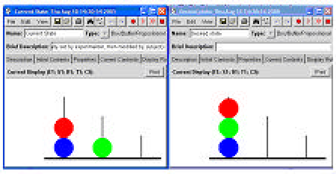
Task completion was signalled explicitly to the experimenter by means of shaking a toy parrot and making it squawk. [Pilot work revealed that it was not always clear when children felt they had solved the tasks. The toy parrot proved to be a popular and reliable way of allowing the child to signal this.]

Video Tape Analysis

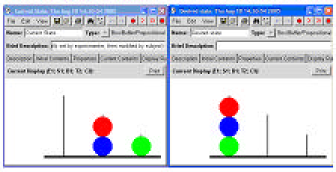
Videotape data was re-analysed for the current study to derive comparison data for the current computer simulations. Performance was scored according to the four criterion measurements: (1) the numbers of moves made on each task (2) the numbers of balls in their correct place (3) whether the child achieved the correct configuration and (4) whether any rule breaks were committed.

Appendix 2: The six ToL tasks

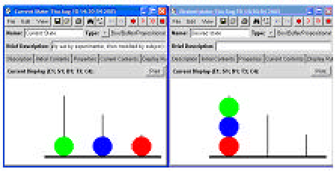
Task 1: Tower-ending (min. 3 move problem)



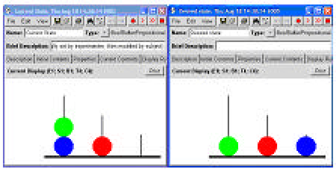
Task 2: Tower-ending (min. 4 move problem)



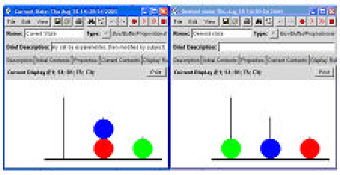
Task 3: Tower-ending (min. 5 move problem)



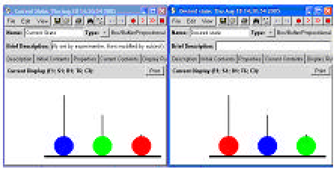
Task 4: Flat-ending (min. 3 move problem)



Task 5: Flat-ending (min. 4 move problem)



Task 6: Flat-ending (min. 5 move problem)



Appendix 3: A printout of the final Older Child model