Knowing How and Knowing That, But Knowing What?

Interference and Transfer in the Acquisition of Problem Solving Skills

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Abstract

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Prior research has suggested that acquisition of problem solving skill may involve mechanisms similar to those of other skill learning (Groff, 1992; Saint Cyr, Taylor, & Lang, 1988; Trepanier, 1989). Theories of skill learning often proceed from the assumption that one learns skilled performance as a sort of habit (Anderson, 1983; Fitts & Posner, 1967) and are often embraced by labels such as implicit learning (Reber, 1989) and procedural learning (Nissen, 1992). Recent criticisms of the implicit learning literature have suggested a conflation between the notions of automaticity of learning and the abstract nature of what has been learned (Shanks & St. John, 1994). The current studies attempt to disentangle the issues of automaticity and abstraction through the use of interference conditions and transfer conditions respectively on the standard Tower of Toronto problem solving task.

In the first experiment, subjects demonstrated preserved learning in each of four transfer conditions: an additional five trials identical to the learning set; five trials of a size coded puzzle; five trials with the second peg as the goal; or five trials solving the puzzle backwards. This suggested that learning in this task is abstract in nature.

The second experiment involved learning to solve the puzzle during ten trials under one of four interference conditions based upon the Stroop task (MacLeod, 1991; Stroop, 1935): no interference; congruent colour and size coding; inverse colour and size coding;

and randomly shuffled colour and size coding. Subjects learned to solve the puzzle equally well under all four interference conditions, though the congruent condition did speed performance. This suggests that learning the puzzle proceeds, at least in part, automatically, without demand for conscious attentional resources.

The third experiment tested subjects in one of four conditions, based upon the extremes of the above two experiment. The presence of interference during learning had no impact upon subjects ability to transfer their learning, thus demonstrating the independence of these issues in this context.

The implications of the findings are discussed in terms of traditional theories of problem solving, procedural and implicit learning, and neuropsychology of skill learning. Future directions are suggested.

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Chapter 1 Knowing How and Knowing That, But Knowing What?

Gilbert Ryle and James' Flywheel of Society

In his 1949 work, *The Concept of Mind*, Gilbert Ryle proposed an important distinction between knowing how and knowing that. Knowing how, according to Ryle, is the hallmark of intelligent behaviour and skilled performance. It is characterised, not by a body of codified principles but rather by a person's ability to perform efficiently.(Ryle, 1949) He contrasted this with knowing that, which refers to a body of information which a person has acquired and can transmit to others verbally. He argued that our tendency to regard cognitive performance only in reference to mental theorising is a result of an intellectualist myth, which would seek to make all skilled performance the result of two separate stages of processing, the deriving of a theory of action and the implementation of that theory to produced skilled performance. This is patently absurd, argues Ryle, for people can behave intelligently, and with acknowledged skill, even in domains, such as humour, for which no clearly formulated theories can be expressed. In reality, people learn to perform skilfully, and it is only in hindsight, or from a third party vantage point, that theories of such skilled performance can be constructed. In other words, according to Ryle, "Efficient practice precedes the theory of it."(1949 p.31)

This would seem to echo much of what William James wrote in *The Principles of Psychology* in the chapter he devoted to habit, or what he called "the enormous fly-wheel of society."(1890 p.116) According to James habits are part of the general nature of the universe. He likens habitual action in organisms, or in their biological processes to the mutability of material substances, such as the breaking in of new clothes, until they are reshaped to their wearer. For James, the ability to acquire habits is extremely adaptive, and fundamentally conservative in that it allows one to fine-tune one's behavioural response to stimuli:

> The first result of it is that *habit simplifies the movements required to achieve a given result, makes them more accurate and diminishes fatigue*. (James, 1890 p.112)

and frees up conscious, volitional resources for other activities.

> The next result is that *habit diminishes the conscious attention with which our acts are performed*. (James, 1890 p.114)

He is careful to distinguish between innate habits, or instincts on the one hand and those that can be acquired, yielding skilled performance, or in Ryle's terminology, knowing how. For James, the crucial learning that takes place in the acquisition of habits is the chaining together of formerly discrete behaviour fragments, conceived by James as under the control of discrete sequences of neural events. Thus in describing learning, he says:

> One may state this abstractly thus: If an act require for its execution a chain, *A, B, C, D, E, F, G*, etc., of successive nervous events, then in the first performances of the action the conscious will must choose each of these events from a number of wrong alternatives that tend to present themselves; but habit soon brings it about that each event calls up its own appropriate successor without any alternative offering itself, and without any reference to the conscious will, until at last the

> whole chain, *A, B, C, D, E, F, G,* rattles itself off as soon as *A* occurs, just as if *A* and the rest of the chain were fused into a continuous stream. When we are learning to walk, to ride, to swim, skate, fence, write, play, or sing, we interrupt ourselves at every step by unnecessary movements and false notes. When we are proficient, on the contrary, the results not only follow with the very minimum of muscular action requisite to bring them forth, they also follow from a single instantaneous 'cue.' (James, 1890 p.114)

The key elements in this description are the idea of proficiency through refinement of procedures, incremental learning, and the chaining of events. According to James, once skills are acquired in this way, conscious mental activity is no longer required for their execution and indeed one may only become aware of the chain of events upon its completion.

> In the present case, no sooner has the conscious thought or volition instigated movement *A*, than *A*, through the sensation *a* of its own occurrence, awakens *B* reflexly; *B* then excites *C* through *b*, and so on till the chain is ended when the intellect generally takes cognizance of the final result. (James, 1890 p.116)

Such discussion seems premonitory to much that has been written in the psychological literature of nearly a century later, touching on issues of procedural and implicit, learning and memory. Accordingly, we now turn to a survey of this literature.

Procedural, Implicit, Learning and Memory

The distinction noted by Ryle has found evidence and application in the experimental study of human learning and memory. In 1968, Corkin demonstrated that the profoundly amnestic patient H. M. could still be taught to perform a pursuit rotor task. His performance over time improved just as that of the control subjects, although he had no knowledge of ever having been trained on the task. She named this preserved ability motor learning (Corkin, 1968). Brooks and Baddeley (1976), tested a heterogeneous group of amnestics on a wide variety of tests ranging from verbal paired associate learning, to Corkin's pursuit rotor task. Their results supported the notion that amnestics could indeed learn new tasks, particularly tasks in the visuo-motor domain when the dependent measure was one of latency. In particular, their amnestic patients showed the same preserved learning performance as H.M. on the pursuit rotor task, and also on a task of timed puzzle construction and only mild impairment on solution of Porteus mazes. Cohen and Squire, in 1980, performed a similar study with the amnesic patient N.A. and several patients suffering from advanced Korsakoff's Syndrome, using a mirror reading task. Their study replicated the earlier findings that, in some cases, where the ability to recall or recognise facts has been lost, the ability to acquire new skills has been preserved.(Cohen & Squire, 1980) Unlike Corkin's task, however, the mirror reading task could not be characterised as motor learning. Clearly this was evidence of a type of non-conscious skill acquisition, perhaps common to many types of skills.

Distinctions and Clarifications of Terms

Squire and Cohen postulated the existence of two dissociable memory systems and named these two parallel memory systems "declarative" and "procedural" memory respectively. This fundamental distinction has been characterised, by others, as the difference between memories and habits (Mishkin & Appenzeller, 1987) or as a distinction between explicit and implicit memories (Schacter, 1987; Schacter, Chiu, & Ochsner, 1993). While traditionally, the above mentioned studies have referred to their subject matters as differing species of memory, we will acknowledge the challenge raised by Lockhart and Blackburn (1993) to more clearly dissociate the terms memory and learning and to use the more correct term implicit learning when speaking of acquisition and implicit memory when speaking of retrieval or test conditions. Under such a dissociation, the results of Corkin (1968) and of Cohen and Squire (1980) should be classified as species of unconscious, or implicit, or procedural learning, without presumption of dissociable underlying memory systems. For convenience, we will also make reference to explicit (declarative) and implicit (procedural) memory, to refer to the separate information acquired by these associated types of learning, in short referring to the distinction raised by Ryle, and without any presumption of underlying structure.

Procedural Memory

Declarative memory refers to fact based knowledge. It functions as a store of information which is accessible to conscious scrutiny and *is* what is classically referred to as memory in studies using recall of information or recognition as the task domain. It is assessed using explicit tests of memory (Tulving, 1985) and has been shown to be influenced by level, or type of encoding. It degrades over even short retention intervals and is subject to proactive or retroactive interference, and it demonstrates transfer across modalities (Schacter & Graf, 1989). In Tulving's ternary classification it corresponds to both semantic and episodic memory, which in turn correspond to noetic and autonoetic levels of consciousness (Tulving, 1985).

Procedural memory is seen as being acquired slowly and incrementally, by trial and error with gradual refinement, in contrast to declarative memory's nearly instantaneous encoding. It can only be tested implicitly by reduced reaction times or increased accuracy across trials (Lewicki, Czyzewska, & Hoffman, 1987; Nissen, 1992). Further, it has been shown to be nearly everything that declarative memory is not. In contrast with declarative memory, procedural memory is relatively immune to manipulations of type or level of encoding; it persists with little change over even very long retention intervals; it is less susceptible to proactive or retroactive interference; and it demonstrates transfer only in very limited circumstances (Cohen, 1984; Schacter, 1989). In addition, it is better acquired through initial over-training (Schendel & Hagman, 1982) than through periodic refreshing (Schacter, 1989). Procedural memory corresponds to anoetic consciousness in Tulving's ternary classification (Tulving, 1985) or to truly unconscious processing in Kihlstrom's tripartite division of the cognitive unconscious (Kihlstrom, 1987).

Procedural Learning

It has been argued that procedural mechanisms might be involved in the abstraction of rules from an environment. Lewicki, Czyzewska, & Hoffman, (1987) demonstrated that subjects could learn to predict the position of a given display based on rules embedded in the previous six displays even though the subjects denied any knowledge of the rules used. While Lewicki et al have interpreted this as evidence of implicit learning of rules it has recently been pointed out that partial knowledge attained from only one of the preceding six trials would be sufficient to produce behaviour at the levels reported. Such learning would not, then, consist of rules abstracted from the stimuli, but only of instances of stimuli themselves, sufficient for above chance predictability (Perruchet & Pacteau, 1990; Perruchet, Pacteau, & Gallego, 1997; Shanks & St. John, 1994). The question of whether procedural learning involves the abstraction of rules or merely the recording of instances is central to the present research.

Willingham, Nissen and Bullemer (1989) performed a study similar to that of Lewicki et al, but using a more sophisticated procedure for assessing rule knowledge. The Serial Reaction Time (SRT) test developed by Nissen and her colleagues (See Nissen, 1992 for a review) has been used to demonstrate the ability of subjects to derive abstract information from a training session in the absence of conscious awareness. In her model task, subjects are presented with an array of four (or more) spots on a computer screen. The spots light up in a sequence, which the subjects must reproduce. In the repeating sequence condition, every *n*th sequence (e.g. 7th) is constant. Over the course of time, subjects display unconscious acquisition of the sequence. They demonstrated that subjects could learn embedded sequences but could not accurately reproduce them, thus demonstrating objectively that the subjects had internalised the rule structure without conscious awareness or access. Indeed it has been demonstrated that subjects can be trained procedurally to master new skills even in cases where they can not consciously recall being trained (Cohen & Squire, 1980; Squire, 1987; Squire & Butters, 1992).

Implicit Memory

Starting largely with the works of Graf and Schacter (Graf, 1987; Graf & Schacter, 1985, 1987; Schacter & Graf, 1986), the field known as Implicit Memory quickly blossomed into something of a mini-industry within cognitive psychology during the 1980s and early 1990s when the newer imaging technologies took pride of place (Cabeza & Nyberg, 2000). It has not been completely abandoned, even now, and still retains a permanent place in modern reviews of memory (See for example Goldman Rakic et al., 2000; Vicari, Bellucci, & Carlesimo, 2000; Zacks, Hasher, & Li, 2000). During it's heyday, some 800 papers were published within this field, mostly on the topic of priming (Shiffrin, 1999). Put simply, experiments in implicit memory seek to show a dissociation, between performance of subjects on test trials which involve material presented earlier in an incidental way, and without instruction to remember, from performance on test trials involving novel stimuli. The concept is that somehow the earlier exposure to the stimuli (or associations, etc. depending on the species of priming under discussion) has a facilitative (or inhibitory) effect on subsequent performance measures (usually latencies).

The field has been summarized quite successfully, in the now somewhat dated review papers by Schacter (Schacter, 1987; Schacter et al., 1993) in which the following properties are said to be true of such implicit memories: They are acquired slowly and incrementally, they are immune to manipulation of type or level of encoding/processing, they persist with little loss over delay, they are not susceptible to interference (proactive or reactive) and show limited transfer across domains or modalities. While there has been much heated debate in this literature about such topics as whether implicit memories actually constitute a different kind of memory, perhaps sub-served by different brain structures, or functional processes, such questions seem beyond the scope of this review.

Indeed, while there are certainly many similarities in the properties listed for implicit memories and the other products of learning discussed in this chapter, with the implicit memory field's focus on the nature and properties of established memories (the primes) rather than on the learning processes itself, it would seem to be largely irrelevant to the discussion at hand. Accordingly, we now turn to the field of implicit learning, which at least promised to be more closely aligned with our discussion of habits and skilled performance.

Implicit Learning

The classic research suggesting implicit (or procedural) learning of an embedded rule structure is that of artificial grammar learning (See Reber, 1989 for a review). In an artificial grammar experiment, subjects are typically presented with nonsense strings of consonants and vowels, which have been generated according to the rules of a finite-state grammar designed by the experimenter. In the initial studies (e.g. Reber, 1967; or Reber, 1976), subjects were told that they were merely to try and remember the strings, and not informed that the combinations of letters presented were in any way lawful. At test, subjects were presented with new strings of letters, some of which were generated using the same rules and some of which were illegal under these rules. When instructed to pick the strings of letters which belonged with the sets they had been studying, subjects performed significantly above chance at selecting those strings of letters which obeyed the rules and rejecting those which were illegal. Subjects were not able to generate any of the rules, when questioned subsequently. In later studies (Reber, 1989 reviews many of these), subjects were explicitly told during the training phase that the strings obeyed rules and to try and determine them. Despite these instructions, subjects still could not accurately recount any of the rules at test, yet still performed well above chance on the task of selecting legal strings. Reber (et al.) have interpreted these findings as proof of a dissociation between a conscious, explicit system of learning and one which is unconscious, and implicit, and used in the process of rules induction.

Such research has argued that, in addition to a learning mechanism based upon declarative rehearsal, there is a parallel system designed to unconsciously extract abstract information from the environment. While such theories were originally postulated to account for the acquisition of natural language in childhood, through experimental investigations of artificial grammar acquisition, they have been extended into other domains. For example unconscious acquisition of abstract rules has been demonstrated in covariation detection (Lewicki, Czyzewska, & Hill, 1997), acquisition of transitive relations (Lewicki, Hill, & Czyzewska, 1994), prediction of target position on the basis of prior, unconsciously learned sequences (Lewicki et al., 1997; Lewicki et al., 1987; Lewicki, Hill, & Bizot, 1988; and Lewicki, Hill, & Czyzewska, 1992 for reviews of this literature; Stadler, 1989), and unconscious acquisition of a sequence of moves in a serial reaction time task which has been discussed above, under procedural learning (Knopman & Nissen, 1991; See Nissen, 1992 for a review; Willingham et al., 1989).

This research has been the focus of several sound criticisms, for example that by Shanks and St. John (1994; 1996). In brief, they criticise the studies for failing to adequately demonstrate that their explicit and implicit tests were equally sensitive, and more importantly for conflating the issue of what was learned with how it was learned. Subjects in the Reber paradigms, we are told, would frequently demonstrate explicit knowledge of sub-strings and pairs of letters, the possession of which, argue Shanks and St. John, would be more than adequate to explain subjects' performances, without need to postulate the induction of the rules used to generate the letter strings (See also Perruchet, 1994; Perruchet & Pacteau, 1990; Perruchet et al., 1997 for a similar series of critques). Indeed recent simulation studies have born out the fact that such exemplar specific knowledge is sufficient to produce the sort of transfer of learning found in the Reber paradigm (Redington & Chater, 1996). However, in a study using a more sophisticated process analysis it was found that human subjects acquire both exemplar specific and abstract knowledge during implicit learning (Knowlton & Squire, 1996).

Implicit learning has been characterised as based upon a system operating in parallel with the declarative memory system (unlike the serial model of Anderson, 1983; Anderson, 1988) and which operates faster and in a structurally more sophisticated way, allowing for the efficient processing of multidimensional and interactive relations (Lewicki et al., 1992). Further this system has been shown to exhibit fewer individual differences than the declarative system and to be uncorrelated in its function with such global measures of individual difference as IQ (Reber, Walkenfeld, & Hernstadt, 1991). Finally, it has been demonstrated in various neuropsychological contexts to be robust in the presence of the sort of medial temporal damage that typically impairs the declarative memory system (See Nissen, 1992 for just one such review), while showing deficits in response to dysfunction of the basal ganglia through disease (Knopman & Nissen, 1991; Saint Cyr et al., 1988 among others), or pharmacological intervention (Perretti, Danion, Kaufman-

Muller, & Grange, 1997) as well as dysfunction of supporting frontal cortical areas (Moreaud, Naegele, Chabannes, & Roulin, 1996).

Automaticity

One of the features James ascribed to habit is that it functions automatically. That is to say, while we may deliberately practice a given skill, the translation of that practice into eventual effortless, skilled performance happens as the result of an automatic learning mechanism (James, 1890). From the work of Fitts and Posner (1967) on, this focus on the non-conscious, automatic component in skill learning has been stressed in such tasks as reading (LaBerge & Samuels, 1974), rapid response, search and matching (Posner & Snyder, 1975), verbal intelligence and individual differences (Hunt, 1978), selective attention, short-term memory search, and attention (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

Lynn Hasher in her landmark paper on automatic processes discusses the distinction between innate automatic processes, and those that are acquired. In general she proposed a series of criteria for automaticity. According to her, automatic processes: operate continuously; cannot be improved upon by additional practice; do not require awareness; cannot be inhibited either wilfully or by external interference; and their products are available to consciousness though their processes are not (Hasher & Zacks, 1979). In so doing, she has incorporated many of the features of earlier models such as that of Posner and Snyder in which automatic processes occur without intention, without necessarily giving rise to awareness and without interference from or interfering with higher order cognitive processes (1975). There are also some features in her model that are similar to one of the two species of controlled processes proposed by Schneider and Shiffrin, namely the veiled controlled processes which occur quickly, and without necessarily being open to awareness (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

While there has been much debate about the nature and extent of automatic processing in cognition, it seems certain that at least some processes must require no or minimal conscious control, and of these the learning mechanisms involved in the acquisition of habitual skilled performance seem likely candidates.

A Neural Substrate for Procedural Learning

It has been theorized that unlike declarative memories which are thought to be subserved by the hippocampus, procedural memories or habits are refined and encoded by the basal ganglia thalamocortical system (Cohen, 1984; Mishkin & Appenzeller, 1987). Accordingly one would expect that damage to this cortical appendage, as in PD, would result in impairment on tests of procedural memory.

Indeed, using a pursuit rotor paradigm similar to Corkin's (1968) it has been shown that patients with Parkinson's Disease (PD) (Bondi & Kaszniak, 1991) and indeed early in Huntington's Disease (HD) (Heindel, Butters, & Salmon, 1988; Heindel, Salmon, Shultz, Walicke, & Butters, 1989) are impaired in learning to keep their stylus on target. Frith, Bloxham and Carpenter (1986) have employed an even more sophisticated test of "motor learning" involving using a joystick to track semi-predictable stimulus patterns in either a normal or mirror reversed control condition. PD patients were impaired relative to normal controls on both halves of the test but they showed particular impairment during the initial 1 minute practice session when most normals managed to master the task easily. These studies all demonstrate that basal ganglia lesion produce impairments of procedural learning in the motor domain but one could argue that its always been assumed that the basal ganglia play a role in motor control.

In the nineteenth century, anatomists identified two primary motor systems in the central nervous system. The pyramidal system was the result of output from cells in primary motor cortex, crossing at the pyramidal decussation in the hindbrain and descending the spinal cord to enervate the motor neurons for distal body movements, involving limb responses. Contrasted with this was the so-called "extrapyramidal" system, originating in the basal ganglia and descending via separate fibres and multisynaptic junctures to affect postural control, and other axial functions of the motor neurons (See Denny-Brown, 1962 for a classic statement of this position). In the latter half of the twentieth century this conception has been abandoned, largely due to the absence of a second descending system of fibres (Brodal, 1963), thus necessitating any basal ganglia influence on movement to be transmitted via the pyramidal system as well .

Certainly, it is acknowledged that the basal ganglia play a role in motor activity. There are motor impairments associated with disorders of the basal ganglia such as Huntington's Chorea and Parkinson's Disease. The basal ganglia have been conceived of as playing a role in creating and modulating movement patterns, but more interestingly they have also been implicated in various cognitive processes. Many theories of attention, visuospatial function, executive function and procedural learning now incorporate the basal ganglia as key elements (Dubois, Boller, Pillon, & Agid, 1991; Owen & Doyon, 1999; Saint Cyr & Taylor, 1992; Saint Cyr, Taylor, & Nicholson, 1995).

Traditionally, anatomists and physiologists have conceived of the basal ganglia as a funnel, with input from the entire cortex being condensed at each level of processing from the striatum (caudate and putamen), through the globus pallidus/substantia nigra and on to the thalamus. Upon cursory examination such a function would seem logical as there is a considerable reduction in mass of neurons at each "stage" in the above sequence. More recently, however, anatomists have argued that the various structures of basal ganglia act more in parallel, and as multichannel structures, processing functionally segregated parallel circuits.

By the latter half of the 1980s at least five such segregated, parallel, closed, basal ganglia-thalamocortical circuits had been proposed based on anatomical study (Alexander, DeLong, & Strick, 1986). Each of these circuits consists of an area(s) of cortical input, feeding the neostriatum (caudate or putamen), in turn linked with the exterior and interior globus pallidus (GPe and GPi respectively) and substantia nigra pars reticulata (SNr) and finally feeding inputs to thalamic nuclei afferenating the original (or closely related) cortical region. There is a preservation of somatotopy and neuronal specificity at each stage of the loop, suggesting that each loop is actually composed of multiple parallel channels. There is however, some evidence for at least some integration and association, particularly in the pallidum whose neurons are typified by large disk shaped arborizations (Alexander, Crutcher, & DeLong, 1990; Alexander et al., 1986; but see also Parent, 1990). The specific circuits described so far, differ in their connections at each stage of the above sequence, and presumably subserve different functions as well. While this simple five-fold, parallel and segregated, structure has come under question (Saint Cyr, Ungerleider, & Desimone, 1990; Selemon & Goldman Rakic, 1985) with renewed evidence of cross-talk amongst channels previously assumed to be completely segregated (Flaherty & Graybiel, 1995; Parthasarathy, Schall, & Graybiel, 1992), there is nonetheless some value to continuing this taxonomy, even as it is acknowledged to be only an approximation (Percheron & Filion, 1991).

First, and perhaps best understood, is the motor loop. Inputs to this loop are from the supplementary motor area, arcuate premotor area, primary motor and primary somatosensory cortex. The neostriatal target of this inflow is the putamen. The putamen in turn projects to the ventrolateral section of the GPi and caudolateral segment of the SNr. Finally, these areas project to the ventrolateral nuclei of the thalamus (both pars medialis and pars oralis). In turn these regions project to supplementary motor cortex.

The second of these circuits is the oculomotor loop. The principle cortical input (and outflow target) are the frontal eye fields, though additional input is received from the dorsolateral prefrontal and posterior parietal cortex. These areas project primarily to the body of the caudate nucleus. In turn, these striatal neurons project to the caudal dorsomedial GPi and ventrolateral SNr. The thalamic component of this circuit are the medialis dorsalis pars paralamellaris and the lateral segment of the ventralis anterior pars magnocellularis.

Third, there is the dorsolateral prefrontal circuit. As the name suggests, the principle cortical component of this circuit is the dorsolateral prefrontal region, though additional enervation is provided by posterior parietal and arcuate premotor areas. This circuits runs through the dorsolateral head of the caudate to the lateral dorsomedial GPi and rostrolateral SNr, finally projecting to the ventralis anterior and medialis dorsalis (both pars parvocellularis) nuclei of the thalamus and thus back to the dorsolateral prefrontal cortex. This circuit has been implicated in the sorts of executive dysfunctions reported below.

The fourth circuit is the lateral orbitofrontal circuit, which has as its primary cortical region the lateral orbitofrontal cortex. Supplementary inputs to this circuit arise in the superior and inferior temporal gyri, and the anterior cingulate. The ventromedial head of the caudate passes on these inputs through the medial dorsomedial GPi and rostromedial SNr, to the medial segment of the ventralis anterior and medialis dorsalis (both pars magnocellularis) nuclei, which close the loop with the lateral orbitofrontal cortex.

Finally, there is a circuit arising in the anterior cingulate cortex with additional inputs furnished by hippocampal and entorhinal cortices as well as the superior and inferior temporal gyri. This input is channeled through the ventral striatum (including the nucleus accumbens), the rostrolateral GPi, ventral pallidum and rostrodorsal SNr, to the posteromedial region of the medialis dorsalis which in turn innervates the anterior cingulate.

The neurochemistry of the basal ganglia-thalamocortical circuits demonstrates two important principles of organization: disinhibition and negative feedback via opponent processes. The striatum projects to the output nuclei of the basal ganglia via two channels, one direct and the other indirect. The direct channel involves striatal neurons using the neurotransmitter γ-aminobutyric acid (GABA) and substance P to inhibit GABAergic neurons in the GPi/SNr which in turn inhibit thalamic excitatory (glutamatergic) enervation of cortex. Thus striatal activity in the direct path serves to disinhibit excitatory thalamocortical activity. The indirect channel involves GABAergic striatal neurons (with enkephalin) inhibiting GABAergic neurons in the GPe, which in turn inhibit excitatory glutamatergic neurons of the sub-thalamic nucleus (STN) that project to GPi/SNr. Thus striatal activity in the indirect path serves to facilitate GPi/SNr inhibition of thalamocortical activity. These two opposed systems are modulated by dopaminergic inputs to the striatum from SNc which are excitatory for neurons in the direct channel but inhibitory for neurons in the indirect channel. The whole system then is set up to produce tonic inhibition of the thalamocortical afferents with potential phasic disinhibition (Alexander & Crutcher, 1990). These patterns of neurochemical activation and inhibition are essential to understanding the mechanisms of basal ganglia dysfunction such as Parkinson's Disease and Huntington's Chorea and the different presentations of symptoms with these dysfunctions.

In summary then, the anatomy of the basal ganglia can be conceived as a set of functionally segregated parallel circuits, in which information from cortical centres of planning and action are integrated with polymodal sensory and proprioceptive information and coupled with limbic processes of motivation and reward. The outflow of these "complex loops" is directed at the initial cortical centres mentioned above, and thus the basal ganglia is ideally situated to provide ongoing executive sequencing and maintenance of cortical activity. The neurochemical and neuroanatomical interconnections of the basal ganglia thalamocortical circuitry is designed to provide tonic inhibition of thalamocortical excitation, maintaining the cortical status quo, while remaining energized to respond to changes in environmental or proprioceptive stimuli with phasic increases in thalamocortical activity. In essence then, the anatomy of the basal ganglia supports the notion of a functional cortical appendage responsible for supporting the planning functions of the neocortex.

The search for a model of basal ganglia function among human neurological patients has concentrated on instances of the so-called subcortical dementias such as Huntington's Disease (HD), Progressive Supranuclear Palsy (PSP), and Parkinson's Disease (PD). Additionally, patients suffering from hemiballism following stroke, psychiatric patients suffering tardive dyskinesia following therapy with major tranquilizers, and patients suffering from accidental overdose on 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP) have all been considered.

Recently, there has been a great deal of interest in evidence of executive dysfunction in PD. Studies using tests traditionally believed sensitive to frontal lobe dysfunction have been used to assess dysexecutive syndromes in PD, often with surprising results (Saint Cyr, Groff, & Taylor, under review; Saint Cyr, Taylor, & Lang, 1993; Taylor & Saint Cyr, 1995). The results of these studies suggest that PD patients do indeed have deficiencies in the formation and shifting of mental sets.

The deficits on tests such as the California Verbal Learning Test and the Bushke Selective Reminding Task all seem to reflect an inability of the PD patients to spontaneously utilize organizational clues present implicitly in the stimulus materials. PD patients do indeed demonstrate a wide range of executive and otherwise "frontal" disturbances. This fact has led many researchers to consider the cognitive impairments associated with PD the result of disrupted information flow through the frontal and prefrontal cortex. As the major targets of processed information from the basal ganglia are the frontal and prefrontal cortices it is hardly surprising that impairments resembling frontal lobe pathology are so prevalent in PD.

In Chapter 2 we will see patterns of frontal-striatal dysfunction correlated with deficits in performance of a traditional problem-solving task. Traditionally, however, much of the discussion of automatic processes and skill learning has been situated in the perceptual/motor domains. More recently there has been an interest in whether the performance on higher-order cognitive tasks such as classical problem solving, might also be characterised as instances of implicit learning. Accordingly we now turn to a brief summary of the literature on problem solving.

Problem Solving

Trial and Error, The Law of Effect, Gestalten und Einstellung

Problem solving has at least as long a history as a domain in psychology as memory or habit. Taking as an arbitrary starting point Thorndike's puzzle box experiments (Thorndike, 1898) much of this early work could be characterised as what would come to be called behaviourist. The essential features of problem solving under this scheme are trial and error search behaviour by the organism, with the environment providing reinforcement of whatever works, what Thorndike refered to as the Law of Effect (Thorndike, 1908). The essential feature of problem solution under all these schemes is the idea that problems are solved in a piecemeal fashion.

Eventually there would be dissent from those that felt that problem solving proceeds through examination of whole problems (Sargent, 1942). The chief supporters of this latter position come largely from the school of Gestalt psychology (Duncker, 1945; Kohler, 1976 originally published in German in 1916; Luchins, 1942). Key to this second conception of problem solving was the notion of reconceptualizing the problem space, and restructuring of the elements of the problem, until a viable solution had been achieved.

Despite the apparent contradictions between these two approaches and the often-hostile critiques levelled by proponents of each against the other, in reality they had much in common. This has caused more than one historian to speculate that the differences between the behaviourist and gestalt traditions had more to do with the temperaments of the researchers than the phenomena under study. With the dawn of the computer age and the cognitive revolution in psychology and allied disciplines, a new formal approach to problem solving was begun.

From Logical Behaviourism to Production Systems

The earliest cognitivist theories of problem solving derive from studies of "knowledge lean" problems (Ernst & Newel, 1969; Newel & Simon, 1972). These are problems in which all the information necessary to solve them is contained in the instructions to the subjects.

The goal of this research was the elaboration of a general algorithm to explain human problem solving behaviour and the generation of a computer simulation (ie. General Problem Solver or GPS) of that algorithm in operation. Subjects were assumed to engage in a series of decision processes constrained by the range of allowed alternatives, collectively referred to as the problem's state space (Ernst & Newel, 1969; Newel, 1980; Reed & Simon, 1976). This process is sub-served by two co-operative processes: understanding and search. Understanding refers to the comprehension of the initial instructions. Specifically it refers to three items of knowledge concerning the problem space: a representation of the initial problem state, a representation of legal operators to change the problem state and an efficient test for the solution state. Search is the active processing of information derived in understanding and is thus driven by both the current problem state and by the internalised rule structure (Newel & Simon, 1972).

More recently, problem solving in a knowledge lean environment has been characterised as a form of procedural learning, but procedural learning of productions (Anderson, 1983; Anderson, 1988; Neches, 1987; Ohlsson, 1987). These process models of problem solving suggest that the rules of a problem are internalized and proceduralized during the initial phases of a problem-solving task. Thus the task is initially represented declaratively; and through manipulation of this representation in declarative memory, implicit rules are generated. This process causes the proceduralization of these rules or productions, condition-action statements that guide a subject's pattern of search and acquisition of understanding during a problem solving task (See Anderson, 1983; and Rosenbloom & Newel, 1987 for some classic examples). Initially, the problem solver works on interpretation of declarative knowledge (i.e. the explicitly stated rules) in the same way one would work through an unfamiliar recipe. Processing at this stage is thought to be slow, effortful and error prone. Eventually, subjects develop efficient productions, whose presence can only be demonstrated implicitly, as subjects' performance becomes increasingly fast, effortless and accurate. Such a system of proceduralization of skills is John Anderson's ACT* theory (Anderson, 1983). These theories have much in common with older stage-based models of motor skill acquisition (Fitts & Posner, 1967; Gentile, 1972) indeed ACT* explicitly owes a theoretical debt to Fitts and Posner's earlier theory. Such a theory has the advantage of explaining subjects' ability to internalise skills which, if solved consciously and serially, would exceed the available resources of working memory (Baddeley, 1986).

In other words, the process of solving a problem involves the proceduralization of cognitive skills, which are productions arising from internalisation of rules, search for available moves, and increasing ability to navigate the problem's state space, all at a non-conscious level. The classic critique of production systems is that they are really only behaviourism under a new guise. Indeed Anderson has been frank in admitting, "the production system is very much like the stimulus-response bond" (Anderson, 1983 p.6).

The Age of Reason?

While it is true that production systems do have more cognitivist terminology (such as goals) they are still very mechanistic in application and behaviouristic in evaluation and can be utilised just as easily to map the behaviour of a thermostat as that of a human subject. Additionally, they are subject to the same criticism as that levelled at Plato's doctrine of ideal forms, namely that between any exemplar and the form could be placed a third, more generic exemplar. Likewise, one could always construct another production system which will more accurately reproduce the idiosyncratic behaviour of one's subjects, and in the absence of any criteria of a production system's success, other than it's match to the behaviour of real subjects, there is no principled reason, not to do so. Despite these failings, there is something to be said for Anderson's strong stance on the issue of what subjects acquire through problem solving experience, namely abstract rules to govern their behaviour; and how they make this acquisition, namely through non-conscious processes.

Implicit Processes in Problem Solving

Research in our laboratory has focussed on precisely this non-conscious acquisition of problem solving skill. As noted above there have been numerous criticisms levelled against the notion of drawing distinctions between conscious and unconscious acquisition in general (Shanks, Green, & Kolodny, 1994; Shanks & St. John, 1994, 1996) and of abstract knowledge in particular (Perruchet, 1994; Perruchet & Pacteau, 1990; Perruchet et al., 1997) leading some to question whether there is any role for implicit processes in problem solving (Lockhart & Blackburn, 1993). Nonetheless we have found patterns of neuropsychological impairment (Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988; Saint Cyr et al., 1995) and process dissociations (Groff & Saint Cyr, 1993; Trepanier & Saint Cyr, 1989) on a classic problem-solving task, The Tower of Toronto, that would seem to support the role of implicit learning in problem solving. Before returning to this specific issue, we should review some of the literature on problem solving tasks, similar to the Tower of Toronto, for additional insights.

Chapter 2 The Three Towers: Hanoi, London, and Toronto in Review

The Early History

A Mathematical Puzzle

In 1883 a puzzle game was published in Paris called *La Tour d'Hanoï* and which purported to be from Tonkin, brought back by professor N. Claus (of Siam), mandarin of the college of Li-Sou-Stian for the purpose of popularizing science. The name was a bit of verbal play on the last name of Édouard Lucas (d'Ameins) a professor of mathematics, who eventually wrote up his game in a collection of mathematical diversions (Lucas, 1893). His game was the familiar Tower of Hanoi, with three pegs, and eight disks arranged in order of size from largest to smallest on the first peg.

Figure 1 The Cover of Lucas' 1883 Game (Stockmeyer, 1997)

The instruction sheet in the box, gives the following as the rules:

> The game consists of moving thus, by threading the disks on another peg, and by moving only one disk at a time, obeying the following rules:
>
> I. -- After each move, the disks will all be stacked on one, two, or three pegs, in decreasing order from the base to the top.
>
> II. -- The top disk may be lifted from one of the three stacks of disks, and placed on a peg that is empty.
>
> III. -- The top disk may be lifted from one of the three stacks and placed on top of another stack, provided that the top disk on that stack is larger (Stockmeyer, 1997).

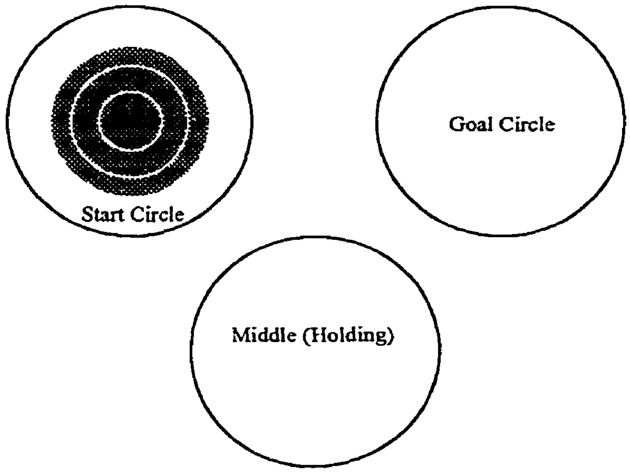
The story presented as the rationale for the game has become part of the lore of psychology, namely that in India a certain group of Brahmin priests have made it their mission to solve a similar puzzle using 64 golden disks. Should they ever complete this work, we are told the world will end, though as Lucas himself points out, solving such a puzzle, even without error, would require 18 446 744 073 709 551 615 moves, which at the rate of one move per second would take over 5 billion centuries (Lucas, 1893). The game instructions makes two other claims which are of particular interest to a history of problem solving: that the solution is always possible, and that the game easily teaches itself, by progressing from simpler problems to more complex ones.

The Disc Transfer Task and Psychology

The Tower came to psychology in the mid-twenties when J. Peterson and his graduate student L.H. Lanier published a series of monographs on racial differences in intelligence and reasoning (Peterson & Lanier, 1929; Peterson, Lanier, & Walker, 1925). In searching for tests of intelligence, speed of processing and reasoning ability that were free of cultural and motivational contaminants, the authors present three tasks: Rational Learning, Mental Mazes, and the Disc Transfer Task. The latter, is simply the Tower of Hanoi in another guise, though with no credit to the earlier mathematical work on the puzzle. The stimuli for this task consists of a cardboard mat on which is inscribed three circles, and a stack of cardboard discs, initially three, in one of the circles.

The instructions given for solving the puzzle are somewhat different than for the original case, however. Subjects are told that they are to recreate the tower of discs on the third circle, while obeying the familiar restriction of not placing a larger disc on top of a smaller disc. They are then explicitly told that they will have to use the other circle (it's not really in the middle, as the circles are arranged in a triangle (see Figure 2)) as a holding place for discs during the solution. Then the experimenter works through a solution in the minimum number of moves, and tells the subjects to attempt to replicate his performance. After solving the puzzle with three discs the subjects move on to a four disc, and eventually a five disc version.

Figure 2 The Disc Transfer Task (Peterson et al., 1925)



Peterson, and his colleagues describe the Disc Transfer Task, conceptually, as a test of ingenuity, mental speed, and reasoning. They employ the task to confirm most of the commonly held biases of their day concerning the relative mental capabilities of black and white children (Peterson & Lanier, 1929; Peterson et al., 1925).

When Hunter (1928) incorporated the Peterson task into his chapter on measures of thinking he described the process by which subjects gain experience with the puzzle. According to him, solving the puzzle is initially characterized as trial and error reinstatement of habits, with some online efficiency improvements. However, the whole task is said to be mediated by language behavior—indeed he cites it as an example of verbal learning—of the verbalized strategies as they are expressed (Hunter, 1928). This notion, of the disc transfer task being essentially verbally mediated, is echoed by Ewert (1932) in discussion of his administration of the problem. He found that increased instructions to verbalize their solution strategies facilitated his subjects' performance on all measures. In particular, the learning curves for errors (examples of rule breaking) and sidetracks (deviations from optimal performance) showed greatly increased efficiency with these increased instructions. The gains were not uniform however, as increased instructions also lead to increased variability. The suggestion was made that perhaps intelligence was the mediating factor (Ewert & Lambert, 1932).

In one of the most cited papers in the disc transfer literature—the one which is often falsely cited as the origin of the Tower of Hanoi in psychology—the impact of verbalization on performance is explicitly tested and found to improve not only performance measures, but also subjects' ability to respond intelligibly to debriefing questions, and provide instructions for novice solvers (Gagné & Smith, 1962).

In addition to the impact of verbal mediation on performance on the disc transfer task, subsequent investigations found an interference effect due to instructions which set the subjects for speed (May et al., 1957). However, it has not always been the case that this puzzle interferes with other cognitive tasks, in fact it was found to facilitate a simultaneous temporal interval estimation task (Essman, 1958).

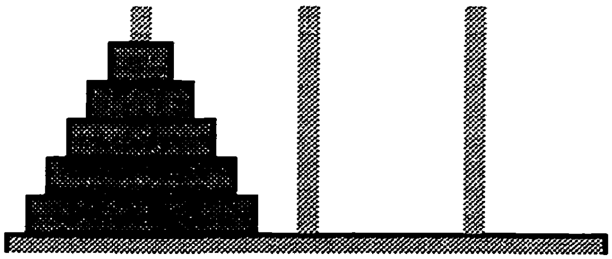
In the early thirties, Peterson began a second series of experiments with the disc transfer task, this time investigating the nature of generalizability from one instance of the task, to another more complex version. His primary interest was the question of whether repeated exposure to tasks of varying difficulty, ranging from one to five discs, would allow subjects to learn the abstract mathematical principle governing the relationship between the number of discs and the number of moves required for optimal solution. Few subjects were able to generate the algorithm (2^n-1) despite repeated practice. Perhaps more interesting, from the perspective of verbal mediation of the task, he found that subjects could not generate intelligible or useful instructions for novice subjects despite their extensive experience (Peterson, 1933). The specific issue of generalizability, and transfer of training was undertaken by Cook, who found that experience on more complex versions of the task improved the rate of learning simpler puzzles, though not vice versa (Cook, 1937) unless the transfer task was composed of the simpler training tasks (Cook, 1939).

Thus it can be seen that it is under the rubric of the disc (see above) or disk (Brousek, 1971; Essman, 1958; Klix & Rautenstrauch Goede, 1967) transfer task that many of the future directions of towers research and theoretical development have happened. Unfortunately, this tradition has been largely lost to those who begin their surveys with the Tower of Hanoi at Carnegie Mellon. The disc transfer name, has maintained some popularity in Europe, however, where it has been used in mathematical studies of learning algorithms (Klix, Neumann, Seeber, & Sydow, 1963; Klix & Rautenstrauch Goede, 1967), psychological studies of children's intelligence (Brousek, 1971) and problem solving ability (Piaget, 1976). It has also been used in studies of demand characteristics of problem solving tasks in general (Stinessen, 1975). Nonetheless, it is certainly true, that this task became most popular under its original name, falsely attributed to Gagné and Smith (1962) and thus it is to this incarnation of the task that we now turn.

The Tower of Hanoi

In the classic presentation of this problem, a subject is presented with a stack of five disks arranged from largest to smallest on the left-most of three pegs. The problem is to move the entire stack to the rightmost peg, which places it in the category of MOVE problems (Kotovsky, Hayes, & Simon, 1985). While making these moves subjects must obey only two rules. First, only one disk may be moved at a time; and second one must never place a larger disk on top of a smaller disk. The complexity of the problem can be varied simply by changing the number of disks in the stack, or by developing isomorphs of the problem with the same state space but different surface features, such as the familiar Missionaries and Cannibals problem some of which can take as much as sixteen times as long to solve (Kotovsky et al., 1985).

Figure 3 The Tower of Hanoi



Early Theories

The earliest references to the Tower of Hanoi, under its original name, are also part of the disc transfer literature (Klix et al., 1963; Klix & Rautenstrauch Goede, 1967) and in Europe the two names continue to be used interchangeably for some time (Piaget, 1976). Klix investigates the Tower as an example of a problem solving task, elaborating upon both algorithms for solution of the task (Klix et al., 1963) and upon the cognitive components necessary for solution, proposing both a local strategic component and an aim-analytic component.(Klix & Rautenstrauch Goede, 1967) Similar suggestions are made by Sydow (1970) in his survey of work done during this period at Humbolt University in East Berlin though he puts more emphasis on the role of memory processes in the ongoing comparisons necessary for solution.

In direct contrast to Klix's work on algorithms for problem solution, Zastavka (1971) engages in the first use of a production system to resolve the dispute between possible approaches to solution. His analytical comparison of 2 methods (Heuristic and Algorithmic) concludes that the algorithmic method is faster but single-purpose only; the heuristic method slower but more general and flexible. The use of production systems to analyse possible solution strategies will figure prominently in the history of this task.

Problem Solving and Production Systems Redux

Clearly, there are many different strategies that could be employed to solve this problem. Simon (1975) has identified four possible ways one could attempt to solve this problem consciously.

First, one could employ a goal recursion strategy (known as Means-Ends Analysis), realising that to solve the problem one must move all but the largest disk to the middle peg first, one would work towards this subgoal. Successfully transferring the largest disk to the goal peg, and then transferring the rest of the stack to the goal peg would follow this. This strategy lends itself to development as a production system and has proven popular in attempts to model subjects' performance with formal production system algorithms (Anzai, 1987; Anzai & Simon, 1979). In addition it is consistent with the observation that the subjects' performance on the task seems to be divided into two distinct phases: an initial search phase terminating in the solution of the subgoal, and a final path phase characterised by planned pairs of moves and more efficient and accurate moves in general (Kotovsky & Fallside, 1989; Kotovsky et al., 1985). It has the disadvantage of requiring subjects to imagine the subgoal of having all disks but the largest on the middle peg which may be possible on the traditional Tower of Hanoi where subjects can visually manipulate "pyramids" of disks (in fact, verbal protocol analysis suggests that subjects do precisely this Anzai & Simon, 1979). It seems that such a strategy is unlikely to work for other isomorphs of the Tower where such visualization is unlikely (Kotovsky et al., 1985; Saint Cyr et al., 1988).

Two other strategies proposed by Simon can be classified as perceptual. In the simplest of these strategies one merely tries to move all disks smaller than the largest off of the source peg. Repeating this procedure until the largest disk is alone on the source peg. One would then attempt to move all the disks smaller than the largest disk off of the goal peg, repeating that procedure until the goal peg is empty. One would then move the largest disk from the source peg to the goal peg. This simple perceptual strategy has the disadvantage that it is possible for a subject pursuing it to end up in non-terminating loops of moves. A more sophisticated perceptual strategy would be to identify the largest disk that is obstructing the move of the largest disk to the goal peg and planning one's moves accordingly. Such a strategy has the disadvantage of requiring a great deal of forward planning, perhaps exceeding the capacity of a subject's working memory.

The fourth solution proposed by Simon is a move pattern strategy, in which one constructs an algorithm of moving the smallest disk on every alternate move (alternating it with the next smallest unobstructed disk), and of moving it in a constant direction (for a given size of tower). Such a strategy has the advantage of having very low demands on working memory. One need only remember the parity of a given move, and the direction of cycling of the smallest disk. The disadvantages of such a strategy are obvious. The subject must abandon the common sense understanding of the problem and instead work on developing a theory of disk cycling. It would also prove impossible to perform such a move strategy without the perceptual cues (e.g. detecting which disks are unobstructed) required for the previous two strategies. On the surface, then it would seem that none of the strategies proposed so far are likely to explain subjects' behaviour on this task. And as has been earlier demonstrated, such an algorithmic solution would not be generalizable (Zastavka, 1971).

Nonetheless since Zastavka there have been numerous attempts to use the basic production system methodology to study the Tower of Hanoi (Anderson, 1993; Anzai, 1987; Anzai & Simon, 1979; de Vivies, 1999; Rosenbloom, Laird, & Newell, 1993; Simon, 1989). This simulation work has investigated such issues as the traditional quarrel between production systems and algorithmic solutions (VanLehn, 1991), recursion (Er, 1984), solution times (Karat, 1982), and transfer to problem isomorphs (Clement, 1996; Clement & Richard, 1997). At one time, the production system literature, as well as the extensive mathematical literature on this puzzle (see Stockmeyer, 1997, for a review), would have been the major sources of information on the essential features of this task. More recently, however, the task has been applied in a number of clinical settings, and this has allowed the clinical and neuropsychological investigation of the cognitive components of the puzzle. It is to this tradition we now turn.

Frontal Lobes and Planning

The Tower of Hanoi has been employed in a number of clinical contexts (Borys, Spitz, & Dorans, 1982; Mataix Cols et al., 1999; Minsky, Spitz, & Bessellieu, 1985; Schmand, Brand, & Kuipers, 1992 to mention but a few). Investigations have been made of patients with Amnesia (Schmidtke, Handschu, & Vollmer, 1996), whether due to Alcoholic Korsakof's Syndrome (Beaunieux et al., 1998; Butters & et al., 1985; Cohen, Eichenbaum, Deacedo, & Corkin, 1985), Hypoxia (Beatty, Salmon, Bernstein, Martone, & et al., 1987), or Temporal Lobe Injury (Morris, Miotto, Feigenbaum, Bullock, & Polkey, 1997a, 1997b). Typically these studies have demonstrated that Amnestic subjects are nonetheless able to learn the task (Beaunieux et al., 1998; Cohen et al., 1985), though these findings are not without dispute (Winter, Broman, Rose, & Reber, 2001; Xu & Corkin, 2001). It has been demonstrated that Amnestic subjects show a slower rate of skill acquisition on the task (Beatty et al., 1987) and suggested that this may imply a retarded transition to more advanced problem solving strategies, presumably partially dependent on an intact declarative memory system (Schmidtke et al., 1996). In a similar vein, patients with Right Temporal Lesions do show some impairment on more difficult, 5 disk versions of the Tower (Morris et al., 1997a, 1997b).

Investigations of patients with brain injury have most frequently studied Frontal Lobe Injury (Cardoso & Parks, 1998; Denckla, 1994; Glosser & Goodglass, 1990; Goel & Grafman, 1995; Mellier & Fessard, 1998; Morris et al., 1997a, 1997b; Rushe et al., 1999;

Tirapu Ustarroz, Martinez Sarasa, Casi Arbonies, Munoz Cespedes, & Ferreras, 1999). The majority of this research with brain injured patients has focussed on such traditional concepts as executive functions (Cardoso & Parks, 1998; Goel & Grafman, 1995; Leon Carrion et al., 1998; Leon Carrion, Morales, Forastero, Dominguez Morales, & et al., 1991; Parks & Cardoso, 1997), in which, it has been shown that damage to the left frontal lobes produces the greatest levels of impairment on the task (Glosser & Goodglass, 1990). A traditional equation of executive functions with planning has been challenged by some, who see the impairments more as evidence of an inability to resolve goal-subgoal conflicts (Goel & Grafman, 1995). Morris and his colleagues also found significant impairment on the Tower of Hanoi in patients with Frontal Lesions that seemed attributable to goal-subgoal conflicts (Morris et al., 1997a, 1997b) although they characterise this as a type of planning deficit.

Similar impairments have been noted when the patients were subjected to neurosurgical evacuation of large frontal haematomas (Leon Carrion et al., 1998) when administered a computerized variant of the task, known as the Tower of Sevilla (Leon Carrion et al., 1991). It should be noted though that this isomorph's ability to discriminate male and female normal controls on error patterns and learning rates (Leon Carrion et al., 1998) argues against it's being considered a typical isomorph of the Tower of Hanoi, as that task has traditionally not found striking sex differences.

The work with Frontal patients has recently been supported by simulation studies (Cardoso & Parks, 1998; Parks & Cardoso, 1997; Parks, Levine, & Long, 1998; Richard, Poitrenaud, & Tijus, 1993) as well as numerous studies on young normal controls (Betsinger, Cross, & DeFiore, 1994; Brennan, Welsh, & Fisher, 1997; Fillbrandt, 1987;

Kotovsky et al., 1985; Scholnick, Friedman, & Wallner Allen, 1997; Welsh, Satterlee Cartmell, & Stine, 1999). Richard (1993), calls his simulation model, based upon his earlier work with first-grade children (Richard, 1982), a Constraint Elimination Model. According to him, an algorithm that uses a mechanism to eliminate implicit constraints on the problem's state space when subjects reach an impasse in solving the puzzle best simulates the behaviour of novices acquiring the task. Such a model certainly harmonises well with the various goal-subgoal conflict models put forward from the neuropsychological evidence especially since his model explicitly tries to integrate plan based and constraint based approaches to problem solving behaviour. Other simulations (Parks & Cardoso, 1997; Parks et al., 1998) have demonstrated typical patterns of executive dysfunction on the task when left-frontal circuitry is "lesioned" which accords well with the pattern of dysfunction noted in the neuropsychological literature and in direct comparison with patient groups (Cardoso & Parks, 1998).

Kotovsky (1985) with his work on normal subjects also stresses the importance of planning for rapid progress in task acquisition. He is careful, however, to also stress the importance of subjects' automatization of rule-using behaviour as a precursor to effective planning. A similar model is proposed by Fillbrant (1987) although the order is precisely reversed. For him, automatization occurs after a period of planning-intensive behaviour in an effort to reduce the load on working memory. It is my contention, based upon work with the Tower of Toronto, that both positions may be correct and that there are in fact two periods of proceduralization during acquisition of problem solving skill. An initial proceduralization of task constraints necessary for conscious hypothesis testing, and then a later proceduralization of the solution strategies developed during this period.

Planning is also stressed in the literature that compares subjects from different educational backgrounds (Betsinger et al., 1994) and of different cohorts of elderly subjects (Brennan et al., 1997) on problem solving performance. The latter study is particularly interesting in that not only does Brennan analyse such traditional measures as number of moves to completion, but also attempts a somewhat detailed error analysis including measures of self-correcting behaviour and error perseveration over consecutive trials (Brennan et al., 1997). He finds that younger elderly subjects behaviour is indistinguishable from young normal controls (YNC) on simple versions of the task, but that as soon as working memory is challenged using a Tower with four or more disks their behaviour becomes more like that of his older elderly sample (Brennan et al., 1997). At the opposite end of the developmental spectrum Welsh (1991) has also found that age differences on tower performance become most pronounced when using more difficult puzzles. She also situates these differences in terms of planning, noting in another study that her subjects tend to pause during solution at certain critical junctures, names the 1st, 5th, and 9th moves on her four disk Tower of Hanoi (Welsh, 1991). Her participants report pausing to plan, though there is no indication of a relationship between the number or length of these pauses and any measures of the success of their performance. Thus these pauses may have less to do with genuine planning than with the use of inefficient heuristics (Welsh, 1991).

Sub-Cortical Damage and Neurodegenerative Disorders

Other patient groups tested have included those suffering with diseases of the Basal Ganglia such as Sydenham's Chorea (Casey, Vauss, Chused, & Swedo, 1994), Huntingdon's Disease (HD) (Butters & et al., 1985), and Parkinson's Disease (PD) (Daum, Schugens, Spieker, Poser, & et al., 1995). Casey et al., noted that patients with Sydenham's Chorea displayed an impairment of maintenance of spatially constrained motor sequences, including retaining sequences of Tower moves (Casey et al., 1994). Daum demonstrated an impairment in PD patients' acquisition of problem-solving skill that was indistinguishable from her patients with Frontal lesions while both groups showed preserved perceptual learning (Daum et al., 1995). Butters et al., showed that while Early HD patients were as able to learn the Tower of Hanoi as normal controls, patients with more Advanced HD were as impaired on skill acquisition as the amnestic patients discussed above (Butters & et al., 1985).

Additionally, studies of the impact of sub-cortical damage on Tower performance have included patients with Multiple Sclerosis (Arnett et al., 1997), Cerebellar Atrophy (Botez, 1993; Grafman, Litvan, Massaquoi, Stewart, & et al., 1992) and Injury (Daum, Ackermann, Schugens, Reimold, & et al., 1993). Most of these researchers have associated planning deficits on the Tower with subcortical degeneration such as Cerebellar Atrophy (But see also Botez, 1993; Grafman et al., 1992) and with chronic-progressive Multiple Sclerosis (Arnett et al., 1997) similar to that noted above for patients with Frontal Lobe lesions. Daum et al., however, used her findings of spared performance on the Tower of Hanoi for patients with lesions limited to the Cerebellum as evidence against the possible role of the Cerebellum in procedural learning (Daum et al., 1993).

Additionally, neuropsychiatric investigations of diseases thought to have some sub-cortical involvement have been made of patients with Obsessive Compulsive Disorder

(Butters & et al., 1985; Mataix Cols et al., 1999) and Schizophrenia (Bustini et al., 1999; Rushe et al., 1999; Schmand et al., 1992). With the Schizophrenia patients, deficits in problem solving are seen which are distinguishable from the goal-subgoal conflict resolution problems noted above with Left Frontal patients and also when spatial memory load is controlled for (Rushe et al., 1999). A detailed discrimant analysis has yielded a set of two indices on the Tower of Hanoi, initial planning time and illegal moves on the 3-disk version of the task, that together with measures of persevation and failure to maintain set on the Wisconsin Card Sorting Task correctly classifies schizophrenic subjects 87% of the time (Bustini et al., 1999). The work on many of these studies has also supported a role for procedural learning in acquisition of skill on the tower (Daum et al., 1993; Daum et al., 1995; Schmand et al., 1992). While even those that have characterised the deficits of Tower performance as failures of spatial manipulation have nonetheless stressed the role of dysfunctional frontal-striatal circuitry in the impairments seen in OCD (Mataix Cols et al., 1999).

The role of procedural learning has also been borne out by studies with young normal controls (Clement, 1996; Fillbrandt, 1986, 1987; Klix & Rautenstrauch Goede, 1967; Kotovsky et al., 1985; Poulin Dubois, McGilly, & Shultz, 1989; Svendsen, 1991; Vakil & Agmon Ashkenazi, 1997) and with the amnestic patients mentioned above (Beatty et al., 1987; Beaunieux et al., 1998; Daum et al., 1993; Schmidtke et al., 1996).

Numerous studies have also been carried out with pediatric populations (Fireman, 1996; Goodnight, Cohen, & Meyers, 1984; Hwang, 1997; Klahr, 1978; Klahr & Robinson, 1981; McCarthy, 1995; Richard, 1982; Wallner, 1997), and with those at the opposite end of the life course (Brennan et al., 1997; Vakil & Agmon Ashkenazi, 1997). Aside from studies of normal development, studies with children have included those with high IQ (Kanevsky, 1990; Kanevsky, 1994; Planche, 1985), and those with various clinical conditions such as prematurity (Mellier & Fessard, 1998; Wall, 1996), Turner's Syndrome (Romans, 1997; Romans, Roeltgen, Kushner, & Ross, 1997) and Attention Deficit Hyperactivity Disorder (ADHD) (Allegri, Carugati, Montanini, & Selleri, 1995; Aman, Roberts, & Pennington, 1998; Klorman et al., 1999; Weyandt, Rice, Linterman, Mitzlaff, & Emert, 1998).

Additionally, the Tower of Hanoi has seen service in clinical assessment and experimental work with retarded young adults (Borys et al., 1982; Byrnes & Spitz, 1977; Minsky et al., 1985; Spitz, Minsky, & Bessellieu, 1984, 1985; Spitz, Webster, & Borys, 1982; Vakil, Shelef Reshef, & Levy Shiff, 1997; Waeber & Lambert, 1987) and those with milder learning disabilities (Condor, Anderson, & Saling, 1995; Wansart, 1985, 1990; Weyandt et al., 1998; Wilder, Draper, & Donnelly, 1984), including reading disabilities (Condor et al., 1995; Weyandt et al., 1998), the hearing impaired (Luckner, 1992; Luckner & McNeill, 1994), and the visually impaired. (Cole & Pheng, 1998)

The majority of these studies have characterised the Tower as a problem solving task, and many have been engaged in traditional problem solving issues such as isomorphs (Kanevsky, 1990; Kanevsky, 1994; Klahr, 1978; Klahr & Robinson, 1981), transfer of training (Planche, 1985; Solomon, 1997), verbal mediation (Cole & Pheng, 1998; Moreno, 1995; Wilder et al., 1984), social co-operation (Hwang, 1997), and task demands (Goodnight et al., 1984; Spitz et al., 1982; Welsh, 1991). This pediatric work has been focussed on the issues of clinical assessment (Borys et al., 1982; Klorman et al., 1999) and particularly on the identification of clinical and cognitive correlates.(Klorman et al., 1999; Scholnick & Friedman, 1993; Vakil et al., 1997; Wall, 1996) The majority of the developmental work, however, has focussed on executive functions (Harvey, O'Callaghan, & Mohay, 1999; Kanevsky, 1990; Kanevsky, 1994; Planche, 1985; Romans, 1997; Romans et al., 1997; Wallner, 1997; Zhang, 1998) and planning (Bidell & Fischer, 1994; Cohen, Bronson, & Casey, 1995; Condor et al., 1995; Harvey et al., 1999; Klahr, 1978; Planche, 1985; Richard, 1982; Scholnick & Friedman, 1993; Spitz et al., 1984, 1985; Spitz et al., 1982; Wallner, 1997) as well as the closely related issues of metacognition (Choi & Woo, 1996), working memory (McCarthy, 1995; Romans, 1997), and frontal lobe functioning (Aman et al., 1998; Mellier & Fessard, 1998). Several studies have also demonstrated a role for procedural learning (Fireman, 1996; Klahr, 1978; Vakil et al., 1997). In short, the pediatric studies have come to largely the same conclusions as the studies of brain injured and other patient groups, that the Tower of Hanoi is a task that is particularly sensitive to measures of planning and executive functions, with additional support for the role of non-declarative memory systems in the acquisition of solution skill.

The Tower of London

The Tower of London was an isomorph of the Tower of Hanoi designed specifically as a clinical measure of planning deficits, in patients suffering from frontal lobe injury (Shallice, 1982). It's design was initially motivated by the problems encountered attempting to classify the various administrations of the Tower of Hanoi in terms of difficulty (Shallice, 1982). Nonetheless, despite the efforts of a few (Morris, Evenden, Sahakian, & Robbins, 1987; Schnirman, Welsh, & Retzlaff, 1998) particularly those working with pediatric populations (Anderson, Anderson, & Lajoie, 1996; Krikorian, Bartok, & Gay, 1994; Lussier, Guerin, Dufresne, & Lassonde, 1998) there is, as yet, no universally accepted standard administration of the Tower of London. All administrations do, however, follow a few general principles. First, the constraints of the problem are not presented as rules, about which disks cannot be placed on top, but rather in the lengths of the pegs. The stimuli are balls, not disks, and only the first peg is long enough to hold all three. The middle peg can hold two balls, and the third peg only a single ball (See Figure 4.). Some computerised administrations replace the pegs with a display of three "socks" which can hold only one two or three "balls" respectively.

Subjects are instructed that they may move only one ball at a time and that between moves, the balls must be placed on pegs, not on the table, or retained in the hand. Obviously, the traditional goal of the Tower of Hanoi could not be used with this arrangement of pegs, and so the puzzle is actually to move, in the most efficient way, from some common starting position (for example Figure 4.) to one of a sequence of goal states. Each puzzle in the sequence requiring increasing numbers of moves to complete (See Figure 4a. for some examples).

Figure 4 The Tower of London

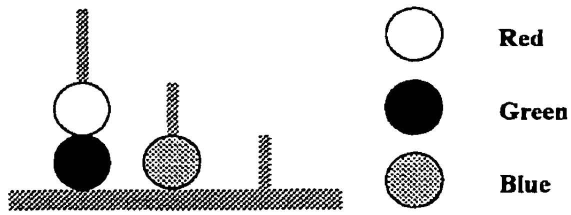
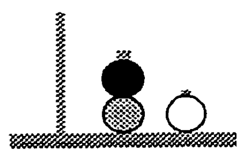
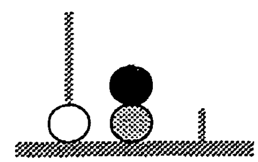


Figure 4a Sample Problems for the Tower of London

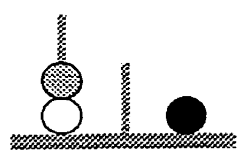
2 Moves to Solution



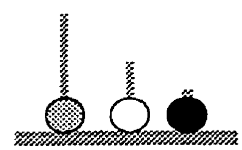
3 Moves to Solution



4 Moves to Solution



5 Moves to Solution



The task is typically considered one of planning, and subjects are instructed to plan out their solution in advance before making the first move. Some administrations give the subject the number of moves in which a given problem can be completed, as a benchmark against which to measure their plan.

A Task for the Supervisory Attentional System

As noted above the task was developed for use with frontal lobe patients as a means of investigating executive and planning deficits. As such, much of the writing on the

Tower of London has concerned its use in clinical assessment (Andreasen, Rezai, Alliger, Swayze, & et al., 1992; Elliott, Baker, Rogers, O'Leary, & et al., 1997; Garnier et al., 1998; Houghton et al., 1999; Keeler, 1995; Krabbendam, de Vugt, Derix, & Jolles, 1999; Molho, 1997; Morris et al., 1987; Morris, Rushe, Woodruffe, & Murray, 1995; Murji & DeLuca, 1998; Purcell, Maruff, Kyrios, & Pantelis, 1997; Wozniak, 1998), and the collection of normative data (Anderson et al., 1996; Schnirman et al., 1998).

There have been studies that have reported clinical correlates of the task (Foong et al., 1999; Houghton et al., 1999; Hughes, Plumet, & Leboyer, 1999; Krabbendam et al., 1999; Krikorian et al., 1994; Miotto, 1994; Molho, 1997; Purcell et al., 1997; Shallice, 1982; Watts, MacLeod, & Morris, 1988; Wozniak, 1998). And many others that have analyzed the cognitive processes involved (Denckla, 1994; Garnier et al., 1998; Hanes, Andrewes, Smith, & Pantelis, 1996; Humes, Welsh, Retzlaff, & Cookson, 1997; Kafer & Hunter, 1997; Keeler, 1995; Molho, 1997; Rousseaux, Godefroy, Cabaret, & Bernati, 1996; Watts et al., 1988; Welsh et al., 1999; Wolffelaar, Zomeren, Brouwer, & Rothengatter, 1988).

Unlike the Tower of Hanoi, very few have identified the Tower of London as a test of subjects' reasoning ability (Oaksford, Morris, Grainger, & Williams, 1996), most have placed it within the domain of working memory (Coull, Middleton, Robbins, Sahakian, & et al., 1995; Green & Rogers, 1998; Luciana, Lindeke, Georgieff, Mills, & Nelson, 1999; Luciana & Nelson, 1998; Welsh et al., 1999). This attribution has been investigated through studies of cognitive processing speed (Lange, Robbins, Marsden, James, & et al., 1992; Morris, Downes, & Robbins, 1990; Morris et al., 1995; Robbins et al., 1998) and through the effect of dual task interference (Phillips, Wynn, Gilhooly, Della Sala, &

Logie, 1999). Such an assessment, places the Tower of London within the realm of central executive tasks, which have characterised the function of the frontal lobes as the operation of a Supervisory Attentional System (SAS) (Shallice, 1982). Accordingly, it is to the use of the task in the investigation of frontal lobe deficits and deficits of planning in particular, that we must now turn.

Frontal Lobes and Planning

The Tower of London has been used in clinical studies of a number of patient groups. It has been tested on subjects with dementia of the Alzheimer type (Goodwin, Conway, Peyro Saint Paul, Glabus, & et al., 1997; Morris et al., 1987; Rainville, Fabrigoule, Amieva, & Dartigues, 1998), as well as Parkinson's Disease (Hanes et al., 1996; Lange et al., 1992; Morris et al., 1990; Morris et al., 1987; Owen, Doyon, Dagher, Sadikot, & Evans, 1998; Owen, Sahakian, Hodges, Summers, & et al., 1995), and other neurodegenerative disorders such as Amyotrophic Lateral Sclerosis (Vercelletto et al., 1999), and Multiple Sclerosis (Foong et al., 1999).

A demonstration has been made of the discriminant validity of the Tower of London for patients with schizophrenia, PD and HD. In comparison with other measures of executive functions (e.g. category fluency, and Stroop interference) strong relationships were found between all three measures suggesting that they tap similar cognitive components (Hanes et al., 1996). In attempts to isolate a possible neurochemical substrate for these components it has been found that L-Dopa withdrawal from PD patients produces symptoms of cognitive slowing, evidenced by increased planning times on the Tower of London, even when corrected for increased motor times (Lange et al., 1992).

When medication is provided to non-medicated mild PD patients there is evidence of improvement in planning on the Tower of London. Specifically, the accuracy of movements after planning is somewhat improved, though the latency for planning is not shortened (Owen et al., 1995).

In a set of drug trials with normal control subjects, noradrenergic activity has been manipulated using Clonidine or Diazepam. Both drugs were found to impair performance on the Tower of London, though Diazepam also produced nonspecific mnemonic impairments, while Clonidine seemed to specifically impair spatial working memory and planning ability (Coull et al., 1995).

The Tower of London has also been used in testing patients with psychiatric disorders such as obsessive compulsive disorder (Veale, Sahakian, Owen, & Marks, 1996), schizophrenia (Andreasen et al., 1992; Delahunty, Morice, Frost, & Lambert, 1991; Hanes et al., 1996; Krabbendam et al., 1999; Morris et al., 1995; Pantelis et al., 1997), and unipolar depression (Elliott et al., 1997; Purcell et al., 1997; Watts et al., 1988).

On a computerized version of the Tower of London test, patients with Obsessive Compulsive Disorider (OCD) performed no differently from controls in the accuracy of their solutions. However, when they made a mistake, they spent more time than the controls in generating alternative solutions or checking that the next move would be correct. Results suggest that OCD may produce a selective deficit in generating alternative strategies following a mistake (Veale et al., 1996).

A study was made comparing the performance of patients with schizophrenia to those with frontal lobe lesions, on the Tower of London. Both groups made fewer perfect solutions and required more time for each solution than normal controls. However the latencies were highest in the schizophrenia group suggesting impairment on sensorimotor components of the task (Pantelis et al., 1997). However, in contrast to deficits seen on the Behavioral Assessment of Dysexecutive Syndrome (BADS) and a modified version of the Card Sorting Task (MCST), the Tower of London did not reliably discriminate schizophrenic patients from normal controls (Krabbendam et al., 1999). Neurocognitive training improved schizophrenic patients' problem solving skills measured on the TOL over time (Delahunty et al., 1991).

Patients with Unipolar Depression showed impaired movement latencies on later trials of the Tower of London task, suggesting deficits in the ability to sustain motor responses (Purcell et al., 1997). Watts, et al., studied two types of lapses of concentration in patients with Unipolar Depression: mind wandering and going blank. It was found that going blank was strongly correlated with increased planning times on the Tower (Watts et al., 1988).

Following Shallice (1982) however, the majority of studies have been of patients with frontal lobe injury (Cockburn, 1995; Denckla, 1994; Garnier et al., 1998; Miotto, 1994; Owen, Downes, Sahakian, Polkey, & et al., 1990; Pantelis et al., 1997; Rousseaux et al., 1996). Indeed, the Tower of London has been used to develop theories of frontal lobe, executive functions along side Wisconsisn Card Sorting test, the Design Fluency Test, the Controlled Oral word Association Test, the Word Fluency, and the Porteus Maze Test (Miotto, 1994).

In a specific attempt to assess the sensitivity of the Tower of London for discriminating different types of focal brain damage following closed head injury. It found that the Tower of London was unable to discriminate different types and locations of brain damage, largely due to strong individual differences among subjects in their ability to solve the puzzle (Cockburn, 1995). Individual differences that have also been found premorbidly among normal controls which significantly reduce the reliability of the test (Welsh et al., 1999).

In contrast, other studies have found patterns of dysfunction among frontal patients. For example, patients with frontal lobe damage, while still able to solve even the most difficult problems within the allowed maximum number of moves, nonetheless took more moves to solve each puzzle, and thus completed fewer puzzles than normal controls (Owen et al., 1990).

The majority of the patient studies involving the Tower have followed Shallice's lead (1982) and characterized the task as one of planning (Baker, Rogers, Owen, Frith, & et al., 1996; Bartok, 1995; Coull et al., 1995; Dagher, Owen, Boecker, & Brooks, 1999; Gilhooly, Phillips, Wynn, Logie, & Della Sala, 1999; Goulden, 1999; Hanes et al., 1996; Hughes, 1998; Hughes et al., 1999; Hughes, Russell, & Robbins, 1994; Kafer & Hunter, 1997; Keeler, 1995; Lange et al., 1992; Luciana et al., 1999; Luciana & Nelson, 1998; Lussier et al., 1998; Morris, Ahmed, Syed, & Toone, 1993; Murji & DeLuca, 1998; Owen et al., 1998; Owen et al., 1995; Passolunghi, Lonciari, & Cornoldi, 1996; Phillips et al., 1999; Rainville et al., 1998; Spikman & Brouwer, 1991; Veale et al., 1996; Ward & Allport, 1997; Watts et al., 1988). In an attempt to validate the Tower of London as a measure of planning, comparisons to a task with a known planning component, the

Porteus Maze Test (PMT) as well as the Wisconsin Card Sorting Test (WCST), the Corsi Blocks, and the Digit Span. The PMT correlated with performance and the Tower, supporting the construct validity of planning. Attentional mechanisms clearly also play a role in solving this puzzle as there was also a correlation with the basal score on the Corsi Blocks. Interestingly, the Tower of London did not correlate with WCST (Bartok, 1995).

In comparing patients with Dementia of the Alzheimer's Type (DAT) it was found that they made three times as many rule violations and solved fewer puzzles than normal controls. The authors interpret this as evidence of a planning deficit (Rainville et al., 1998).

The same conclusion has been reached by experimental studies conducted on young normal controls (Baker et al., 1996; Bartok, 1995; Dagher et al., 1999; Hoptman & Davidson, 1998; Humes et al., 1997; Kafer & Hunter, 1997; Morris et al., 1993; Oaksford et al., 1996; Phillips et al., 1999; Rezai, Andreasen, Alliger, Cohen, & et al., 1993; Schnirman et al., 1998; Ward & Allport, 1997; Welsh et al., 1999; Wolffelaar et al., 1988), as well as studies on normal aging (Garnier et al., 1998; Gilhooly et al., 1999; Robbins et al., 1998; Spikman & Brouwer, 1991), and pharmacological effects (Coull et al., 1995; Morgan, 1998; Young, Sahakian, Robbins, & Cowen, 1999). Recently, in a more traditional study, similar to cognitive work on the Tower of Hanoi it has been shown that verbalization caused slowing, but had no impact on other performance on the Tower of London. Verbal Protocol Analysis showed evidence of a means-ends approach taken by subjects, though older subjects engaged in less complete planning (Gilhooly et al., 1999).

Imaging Studies

These findings have been borne out by a recent series of imaging studies. (Dagher et al., 1999; Elliott et al., 1997; Foong et al., 1999; Goodwin et al., 1997; Levin, Mendelsohn, Lilly, Fletcher, & et al., 1994; Levin et al., 1997; Owen et al., 1998; Rezai et al., 1993; Vercelletto et al., 1999) The various methodologies have included Positron Emission Tomography (Baker et al., 1996; Dagher et al., 1999; Elliott et al., 1997; Goodwin et al., 1997; Owen et al., 1998), Magnetic Resonance Imaging (Levin et al., 1994; Levin et al., 1997; Rousseaux et al., 1996), Magnetic Resonance Spectroscopy (Foong et al., 1999), Single Photon Emission Computerized Tomoraphy (SPECT) (Foong et al., 1999; Goodwin et al., 1997; Morris et al., 1993; Rezai et al., 1993; Vercelletto et al., 1999). Most have used some measure of regional cerebral blood flow during (rCBF) subsequent to the solution of the puzzle as their primary dependent measure (Andreasen et al., 1992; Dagher et al., 1999; Morris et al., 1993; Owen et al., 1998; Rezai et al., 1993).

The Frontal Lobes

Imaging Studies of the Tower of London have also tended to focus on the relationship between the frontal lobes and executive functions, especially planning. A study measuring rCBF in Neuroleptically naïve schizophrenic patients reveals hypofrontality, particularly of the Mesial Frontal (rather than dorsolateral) areas, linked to failure to show increase rCBF in right parietal lobe, shown by normal controls (Andreasen et al., 1992). A similar study using SPECT on normal control subjects, demonstrated bilateral Mesial Frontal activation while performing the Tower of London in contrast to WCST activation of left dorsolateral prefrontal activation (Rezai et al., 1993).

In volumetric studies of children following closed head injuries (CHI), using MRI, it was found that the severity of the injury and age at testing were correlated with performance on several Tower of London measures, especially rule breaking. Further, the volume of the frontal lesion (in contrast to extrafrontal lesions) was correlated with this impairment, even when severity was controlled for (Levin et al., 1994). In a more detailed process analysis of these findings a Principle components analysis of variance identified 5 factors that the experimenters labeled: 1) Conceptual Productivity, 2) Planning, 3) Schema, 4) Cluster and 5) Inhibition. Severity of CHI predicted 1, 2, 4 and 5 while the volume of Left Frontal lesions predicted 3 (Levin, Fletcher, Kufera, Harward, & et al., 1996). Patients' age group (6-8, 9-12, and 13-16 years) also predicted 1, 2 and 5 (Levin et al., 1996). In a later follow up study with these children it was found that volume of Left Frontal lesion could increment the prediction of impairment on the Tower of London, and the WCST, though not on the Twenty-Questions Test beyond measures of CHI severity (Levin et al., 1997).

Sub-Cortical Structures

Some studies have examined sub-cortical structures as well. A Positron Emission Tomography (PET) study was undertaken of depressed subjects using the Tower of London. In contrast to normal controls the patients, who demonstrated the typical performance deficits, did not show the same patterns of cortical/subcortical activation: prefrontal cortex, posterior cortex, cingulate, striaturm, thalamus and cerebellum. The depressed patients did not show significant activation of the cingulate and striatum while activation in the cortical regions was diminished. In addition they failed to show any increased activity of prefrontal, caudate, and anterior cingulate with increased task difficulty (Elliott et al., 1997).

In a subset of patients with probable Dementia of the Alzheimers Type (DAT), **administration of $\alpha(2)$ adrenoreceptor antagonist, Idazoxan (IDZ), results in impairment** on the Tower of London. This impairment was correlated with moderate relative activation in left thalamus and inferior occipital cortex, and decreases of activation in the inferior anterior cingulate and left insula under SPECT (Goodwin et al., 1997).

A study of PD patients using two versions of the Tower of London, the typical planning task and a purely mnemonic, move repetition task was conducted during PET imaging. For the planning task it was found that there was increased rCBF in the Internal Segment of the Right Globus Pallidus (GPi) for normal controls, co-local with the area of greatest attenuation of activation in the PD patients (Owen et al., 1998).

Finally, studies have been undertaken involving patients with neurodegenerative disorders, particularly of white matter, that transcend the cortical/subcortical boundaries. Magnetic Resonance Spectroscopy study of patients with MS found a correlation between reduced N-acetyl aspartate/creatine ratio (NAA/Cr) in frontal white matter and performance on tests of executive function including the Tower of London for many, though not all, of their patients (Foong et al., 1999). The Tower of London has also been used in a prospective study of cognitive deficits in sporadic amyotrophic lateral sclerosis (ALS) using SPECT (Vercelletto et al., 1999).

Imaging of Normal Controls

Similar results have been obtained in studies involving normal control subjects. For example, in one study with subjects solving Tower of London puzzles of increasing complexity, a network of structures thought to support planning on the task was identified using PET imaging. Level of activation was related to the complexity of the puzzles in the lateral premotor cortex, rostral anterior cingulate cortex, dorsolateral prefrontal cortex all bilaterally as well as the dorsal caudate nucleus, though only on the right (Dagher et al., 1999). The authors proposed that these structures form a network subserving planning functions distinct from, but interacting with other networks for visual processing and sequencing of movements. These results are supported by studies with normal controls demonstrating that increased task difficulty is related to increased activity in the Rostral Prefrontal Cortex, while easy tasks are associated with activity in the insula. It may be that increasing the complexity of the Tower of London shifts the task from one of visual manipulation to one requiring more representational, executive effort (Baker et al., 1996).

A certain amount of support has even been gathered from such temporally precise, though spatially imprecise measures as resting Electroencephalogram (EEG) asymmetries. It has been shown that asymmetries, in the alpha, delta and theta bands are correlated with performance on the Tower of London, Verbal Fluency and Corsi Blocks (with recurrent sequences), particularly when recording from anterior electrodes (Hoptman & Davidson, 1998).

Developmental Uses

The Tower of London has been used in a number of studies on pediatric populations (Anderson et al., 1996; Goulden, 1999; Hughes, 1998; Krikorian et al., 1994; Luciana & Nelson, 1998; Lussier et al., 1998; Passolunghi et al., 1996).

The studies have included such populations as those born prematurely (Luciana et al., 1999), and those with congenital disorders such as Turner's syndrome (Temple, Carney, & Mullarkey, 1996). For example, 7-9 year olds who were premature showed longer planning times on TOL as well as other planning, executive problems (Luciana et al., 1999). In contrast, subjects with Turner's Syndrome, while demonstrating impairment on such traditional measures of frontal lobe function as Verbal Fluency, the Stroop task, and Self Ordered Pointing, are nonetheless unimpaired on the Tower of London. This suggests that frontal/executive functions are not unitary or homogenized (Temple et al., 1996).

Additional studies have focussed on children with ADHD (Cornoldi, Barbieri, Gaiani, & Zocchi, 1999; Culbertson & Zillmer, 1998a, 1998b; Houghton et al., 1999; Molho, 1997; Wozniak, 1998). Pediatric studies of ADHD show that the TOL correlates with Children's Executive Funcitons Scale (CEFS) (Molho, 1997). In comparison to normal controls, all ADHD (both predominantly inattentive, and combined) patients were impaired, though only the latter on measures of perseveration and response inhibition on frontal lobe tests such as the Tower of London (Houghton et al., 1999). More recently researchers have proposed an alternative to behavioural classification of ADHD subtypes. An attempt to neuropsychological classify ADHD children into those with predominantly

Dorsolateral Frontal (DF) and Orbitofrontal (OF) symptoms has met with some success. The Tower of London was associated with other measures of DF function and helped discriminate these subgroups (Wozniak, 1998). A maximum likelihood factor analysis was conducted on a number of neuropsychological tests in ADHD. A four factor solution best fit the data, suggesting distinctions among frontal lobe functions related to: 1) Executive Planning/Inhibition, 2) Executive Concept Formation/Flexibility, 3) Psychometric Intelligence, and 4) Memory. A variant of the Tower of London (The Tower of London-Drexel or TOL-Super(DX)) loaded most strongly on the first factor, though there was considerable shared variability between factors 1 and 2 (Culbertson & Zillmer, 1998a). This variant has been shown to be quite discriminative of ADHD (Culbertson & Zillmer, 1998b). It has also been shown to be more predictive than metamemory measures of ADHD patients' performance on memory tasks, where instruction and strategic guidance are provided (Cornoldi et al., 1999).

Studies have also been conducted on children with Autism (Hughes et al., 1999; Hughes et al., 1994), Traumatic Brain Injury (Levin et al., 1996; Levin et al., 1994; Levin et al., 1997) and Learning disabilities (Murji & DeLuca, 1998) including the Reading Disabled (Keeler, 1995). In a cognitive neuropsychological investigation of children with reading difficulty it was proposed that students able to decode but encountering problems with comprehension might have global problems with structuring of responses in many domains. Some evidence for this was found on the Rey-Osterith complex figure, but the Tower of London performance was not different from normal controls (Keeler, 1995).

The paediatric studies have also characterised the test as one of executive functions (Cornoldi et al., 1999; Culbertson & Zillmer, 1998a, 1998b; Levin et al., 1994; Levin et al., 1997; Temple et al., 1996), working memory, and planning (Goulden, 1999; Hughes, 1998; Hughes et al., 1999; Keeler, 1995; Luciana et al., 1999; Luciana & Nelson, 1998; Lussier et al., 1998; Murji & DeLuca, 1998; Passolunghi et al., 1996).

In an attempt to collect normative data from subjects at early developmental stages, through subjects in their undergraduate years, a linear progress in scores on the Tower of London was found. By the time subjects reached grades 6-8 no further statistical differences were found from undergraduate students (Krikorian et al., 1994) however some have shown developmental progress until the age of 16 (Lussier et al., 1998). These findings have been borne out by further attempts at standardization and gathering of normative data which shows that performance on the Tower of London develops throughout childhood with two incremental phases at 7-9 years, and 11-12 years (Anderson et al., 1996). More recent findings indicate a general progression in ability levels on frontal lobe tasks with incremental improvements being seen between 4 year olds, 5-7 year olds and 8year olds. While the 8 year olds were superior to the other groups in their ability to solve complex problems they were not yet performing at adult levels on the Tower (Luciana & Nelson, 1998). All these sets of findings are consistent with developmental and neurophysiological perspectives on periods of maturation of anterior cortical regions. They are also consistent with developmental course of performance on other tasks such as the Porteus Maze Test and Categorization tests (Passolunghi et al., 1996). Further developmental correlates have been found between the impulsivity, initiation and problem-solving scales of the Cognitive Functions Checklist, and such measures on the Tower of London as number of rule-breaking attempts, and overall latency (Murji & DeLuca, 1998).

Children's Executive Functions Scale (CEFS), a 99-item parent report measure developed by the National Academy of Neuropsychology research consortium correlated better with TOL and other measures of executive functions than other parental reports (Goulden, 1999). There have also been demonstrated correlations between TOL and a French adaptation of the 6 elements test (Garnier et al., 1998). Additionally, significant correlations with the Porteus Maze Test have been found in various YNC populations at different developmental stages (Krikorian et al., 1994). Children's growing "Theory of Mind" has been shown to be related to increasing ability at strategic planning and mental flexibility as measured by the Tower of London and other tests of frontal/executive function (Hughes, 1998).

However, it has not always been easy to obtain evidence of cognitive structure from correlations with the Tower of London. In at least one recent study, structural equation modeling of TOL and 6-element test, 20-question test, and the complex figure test, failed to yield an adequate model of the underlying structure of Planning and Problem Solving. The findings suggest that problem solving and planning might be a complex construct not readily amenable to this sort of modeling. Of course, the sample size of this study was quite small for structural equation modeling (Kafer & Hunter, 1997).

Meanwhile, at the opposite end of the developmental life course there have been tests of decline in planning ability during ageing using the TOL (Spikman & Brouwer, 1991). Additionally, patterns of deficits on tests such as the Tower of London have been similar to those seen in frontal lobe or basal ganglia disease among Old Normal Controls aged 74-79 (Robbins et al., 1998).

But is it an Isomorph?

Since it's introduction by Shallice it has been assumed that the Tower of London is a simple isomorph of the Tower of Hanoi. Denkla (1994) lists both Towers (indeed all three as he also mentions the Tower of Toronto) as similar tests of executive functions, along with the Wisconsin Card Sorting Test, tests of Verbal fluency and Figural fluency, multi-trial verbal word list learning, and motor tests.

Conceptually, however the two tasks are quite dissimilar. The Tower of London is perhaps rightly considered a planning task; after all, subjects are explicitly instructed to plan out their solution strategies before making a single move. That they can, is a function of the task demands. The most difficult puzzles administered to subjects typically require only 5 moves to complete--and they only reach those after significant practice solving simpler puzzles. The Tower of Hanoi, on the other hand, requires 7 moves to solve if it has only three disks, and that number increases dramatically, at the rate of 2^n-1, requiring 15 moves for a 4 disk puzzle, and 31 moves for the most commonly administered, 5 disk tower. Such lengthy solutions could not be planned in advance, nor held in working memory even if they could.

Additionally, there is evidence that they tap different cognitive processes as the Tower of London doesn't correlate well with the Wisconsin Card Sorting Task (a known problem solving test) (Bartok, 1995), while the Tower of Hanoi does. They also demonstrate quite different sensitivities with the Tower of Hanoi more likely to suffer from Dorsolateral Prefrontal damage and the Tower of London more sensitive to Mesial Frontal injury. Their patterns of impairment in patients with sub-cortical disease and of performance in pediatric populations are also quite different, though in all fairness it is only the Tower of London that has been extensively developed for administration to children.

Recently, the issue of whether the two tasks are clinically equivalent has come under direct empirical investigation. Humes, (1997) has demonstrated that though there is a significant correlation between the two towers when administered to young normal controls, it is low, around 0.37, largely due to the unreliability of the Tower of London. In all fairness, recent work on the Revised Tower of London has demonstrated internal-consistency reliability of around 0.794 and test-retest reliability of around 0.7 (Schnirman et al., 1998), however the lack of correlation with the Tower of Hanoi is still striking.

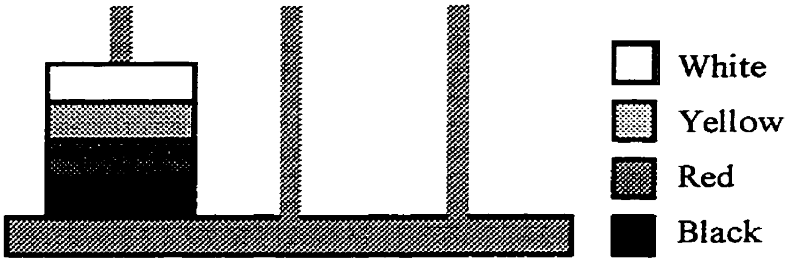
Welsh (1999) administered the two tasks, along with measures of working memory and response inhibition in order to test the equivalence of the two tasks by process analysis. A similar small, though significant, correlation between the two towers was found, and additionally it was shown that while the working memory and inhibition measures together predicted over 50% of the variance on the Tower of London, they were much less predictive of performance on the Tower of Hanoi.

The Tower of Toronto

A New Isomorph for the Clinic

The Tower of Toronto is an isomorph of the Tower of Hanoi in which four disks of the same size are stacked in order of colour (from darkest to lightest: black, red, yellow, white).

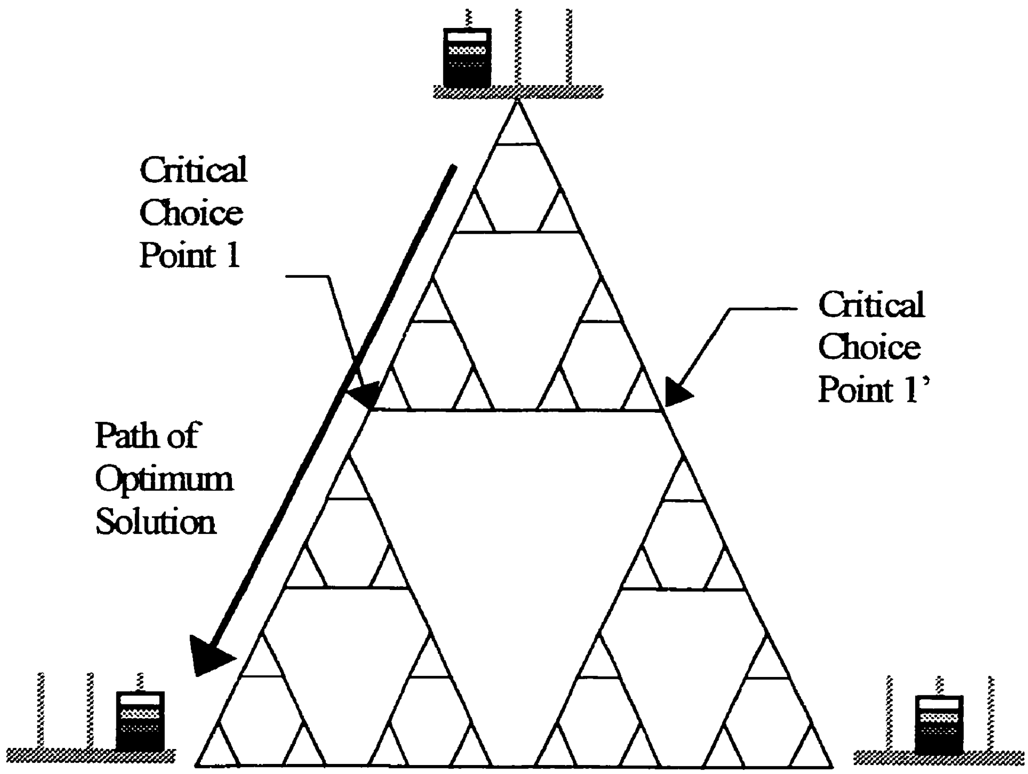
Figure 5 The Tower of Toronto



This task has proven to be a less cognitively demanding version of the original puzzle, suitable for use with various patient groups. (Goldberg, Saint Cyr, & Weinberger, 1990; Michel, Danion, Grange, & Sandner, 1998; Saint Cyr et al., 1993) It has been used in studies of patients with frontal lobe injury (Denckla, 1994) as well as patients suffering from basal ganglia disease such as PD (Saint Cyr et al., under review; Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988, 1993; Saint Cyr et al., 1995; Taylor & Saint Cyr, 1995) or HD (Saint Cyr et al., under review; Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988; Saint Cyr et al., 1995; Taylor & Saint Cyr, 1995). It has also been used with other patient groups such as schizophrenics (Goldberg et al., 1990; Gras Vincendon, Danion, Grange, Bilik, & et al., 1994; Michel et al., 1998), patients with transient global amnesia (Kazui, Tanabe, Ikeda, Nakagawa, & et al., 1995), and developmentally with children who've suffered fetal alcohol syndrome (Regan, 1997). Additionally, the Tower of Toronto has been used experimentally with young normal controls (Groff, 1992; Groff & Saint Cyr, 1993; Trepanier & Saint Cyr, 1989), old normal controls (Trepanier & Saint Cyr, 1989) and in pharmacological studies of the impact of antipsychotic medication (Peretti, Danion, Kauffmann Muller, Grange, & et al., 1997), and cognitive rehabilitation methods (von Cramon, Matthes von Cramon, & Mai, 1991).

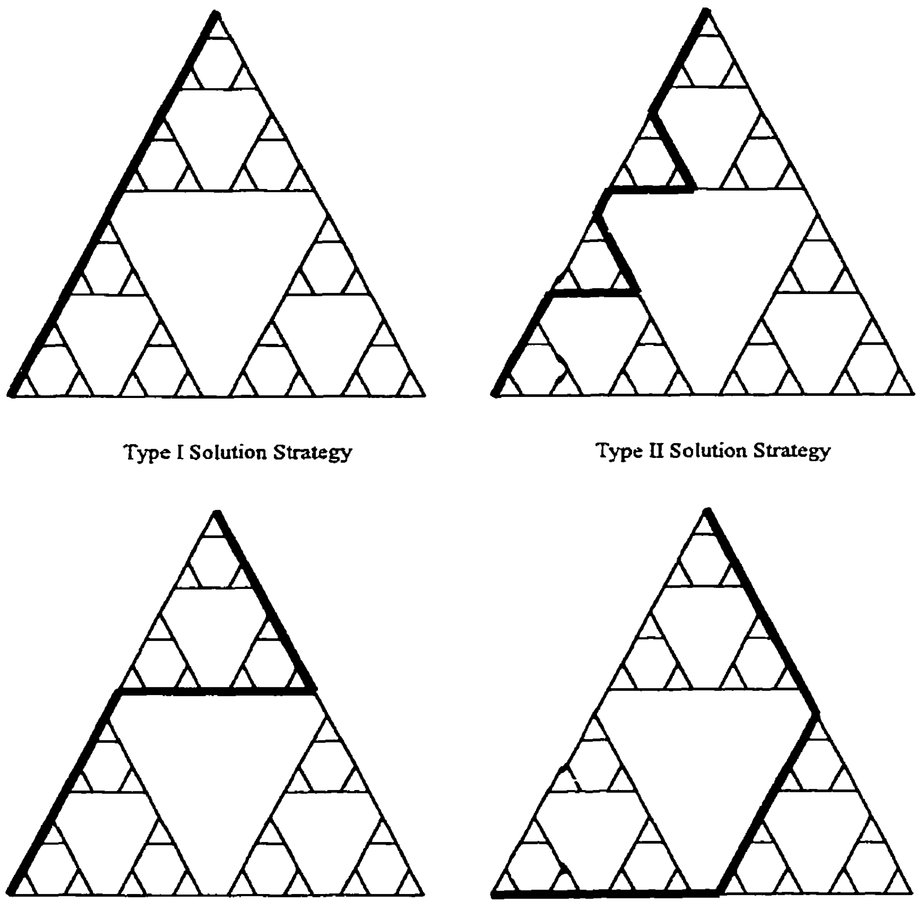
The standard administration of the tower consists of three practice trials on the three-disk problem (TO), followed by two sets of five trials (TT1 and TT2) on the four-disk problem with 1½ hour break between TT1 and TT2.

Figure 6 The State Space of the Tower of Toronto



The state space of the four disk Tower of Toronto (see Figure 6) has been explored in some detail. Subjects tested on this task have been found to employ one of four basic solution approaches (Saint Cyr & Taylor, 1992; Trepanier & Saint Cyr, 1989). These approaches take the form of four basic primary paths to solution represented on the problem's state space (see Figure 7), as discovered by informal and formal cluster analysis techniques (Trepanier & Saint Cyr, 1989). The distinctions among these four primary paths are both quantitative and qualitative. Primary path 1 is the optimal solution pathway. It combines the fewest number of moves to the solution with correct use of the subgoal (marked as critical choice point (CCP)1 on Figure 6) of stacking all but the black disk on the middle peg, allowing the unobstructed movement of the bottom disk from start to goal peg. In addition, subjects employing a path 1 strategy make very few moves off the optimal path, with no extensive loops or backtracking. Primary Path 2 represents a less efficient variation of primary path 1, with increased numbers of off path moves lengthening this otherwise optimally efficient strategy. Primary path 3 begins with an incorrect first move. By placing the initial disk on the goal peg rather than the middle peg, subjects are forced to solve the problem following an inefficient strategy down the right hand side of the state space (for the 4-disk problem). The importance of the first move has been demonstrated by other authors in discussions of the Tower of Hanoi (Kotovsky et al., 1985; Spitz et al., 1982). Solutions using primary path 3 however make correct use of the subgoal described above (CCP1 on Figure 6) and thus return the subjects to the optimal solution path for the remainder of the trial. Primary path 4 also involves an incorrect choice for the first move, but in contrast with path 3, the subjects never return to the optimal solution pathway and must rely on successfully negotiating less efficient sub-goals (represented as CCP1' and the lower right corner on Figure 6 respectively). A fifth solution strategy discovered by Goldberg et al. (1990) is composed of all trials on which the subjects failed to solve the tower in the allotted ceiling of 50 moves. This pattern is characterised by lengthy backtracks and especially by non-terminating loops. It is generally only encountered when testing severely impaired subjects such as the schizophrenic patients tested (Goldberg et al., 1990).

Figure 7 The Four Solution Pathways



Type I Solution Strategy

Type II Solution Strategy

Type III Solution Strategy

Type IV Solution Strategy

Trépanier (1989) demonstrated that subjects' performance improves over the ten trials of the 4 disk problem. Young normal control subjects (YNC) tend to choose better solution strategies in general than Old Normal Controls (ONC) and to make fewer first move errors across trials; however, they demonstrate a greater loss over the 1½ hour delay between trial 5 and 6. This finding suggests that while it is possible to follow a process of conscious hypothesis testing while solving the puzzle (as the initially erratic performance of the YNC suggests they do) there are advantages to pursuing a more procedural trial and error method of solution.

Groff and Saint-Cyr (1993) extended these finding by the discovery of dissociable learning curves for the number of moves to solution across the ten trials and subjects' median move latencies. While the curve of the number of moves across trials showed the classic pattern described above, including the loss over the 1½ hour gap separating trials 5 and 6, the curve of median movement latencies showed a smooth transition through this gap, with no evidence of loss. Groff and Saint-Cyr interpreted this second learning curve as a purer measure of procedural learning on the tower, especially in light of the fact that the curve was abolished by co-varying out the efficiency of subjects' performance (as measured by solution strategy employed on each trial) from the latency curve. Thus the latency curve seems to reflect acquisition of genuine knowledge related to efficiency of performance on the tower and not merely increasing familiarity with the apparatus, etc.

Procedural Memory and the Basal Ganglia

Like the Towers of Hanoi and London, the Tower of Toronto has been characterised as a task measuring frontal lobe function (Moreaud et al., 1996), and executive function in particular (Denckla, 1994; Saint Cyr et al., under review; Saint Cyr et al., 1995). The evidence for these conclusions come from a number of studies seeking both clinical (Regan, 1997) and cognitive (Denckla, 1994; Groff, 1992; Groff & Saint Cyr, 1993; Taylor & Saint Cyr, 1995; Trepanier & Saint Cyr, 1989) correlates of performance on the Tower. This version of the Tower task has also been used on patients with Traumatic Brain Injury (Leon Carrion et al., 1998; Leon Carrion et al., 1991; von Cramon et al., 1991), and CVA (von Cramon et al., 1991).

What is unique to the Tower of Toronto, however, is the high proportion of studies that have been conducted on patients with some form of sub-cortical dysfunction (Saint Cyr et al., under review; Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988, 1993; Saint Cyr et al., 1995; Taylor & Saint Cyr, 1995). This has lead many investigators to emphasise the role of procedural learning in performance on this task (Goldberg et al., 1990; Gras Vincendon et al., 1994; Groff, 1992; Groff & Saint Cyr, 1993; Kazui et al., 1995; Michel et al., 1998; Peretti et al., 1997; Regan, 1997; Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988; Taylor & Saint Cyr, 1995; Trepanier & Saint Cyr, 1989).

The Three Towers

Important Distinctions

As mentioned in the discussion of the Tower of London, the majority of studies using this instrument have focussed on planning and executive functions. Meanwhile, the Towers of Hanoi and Toronto, have both been used to test a wide variety of cognitive components. In part, this seems to be due to the fact that the most common administrations of the Tower of London, involve puzzles whose solutions can be held entirely within working memory, and instructions to subjects to plan out the entire solution in advance. Nonetheless, all three towers have been used quite successfully in clinical contexts.

Similar Findings

Denckla lists all three towers in his chapter on assessment of frontal lobe functioning (Denckla, 1994). As has been seen above, all three towers do show sensitivity to frontal lobe dysfunction, whether investigated through studies of patients with brain injury (Cardoso & Parks, 1998; Cockburn, 1995; Glosser & Goodglass, 1990; Goel & Grafman, 1995; Leon Carrion et al., 1998; Leon Carrion et al., 1991; Miotto, 1994; Morris et al., 1997a, 1997b; Owen et al., 1990; Rousseaux et al., 1996; Tirapu Ustarroz et al., 1999), Alzheimer's disease (Goodwin et al., 1997; Rainville et al., 1998), or indeed in simulation studies (Parks & Cardoso, 1997; Parks et al., 1998). Such studies have emphasized the role of such typically frontal functions as working memory, executive funcitons and planning in particular on tower performance.

What is perhaps more interesting are the studies have been conducted on groups with various sub-cortical pathologies such as PD (Daum et al., 1995; Lange et al., 1992; Morris et al., 1990; Morris et al., 1987; Owen et al., 1998; Owen et al., 1995; Saint Cyr et al., 1993), HD (Butters & et al., 1985; Hanes et al., 1996; Saint Cyr et al., under review; Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988; Saint Cyr et al., 1995; Taylor & Saint Cyr, 1995) or others (Elliott et al., 1997). These studies have helped to shape the notion that there may be implicit processes, particularly some form of procedural learning, at work in the acquisition of this problem solving skill.

Implict Processes in Problem Solving?

Studies with Amnestics (Saint Cyr et al., 1988; Schmidtke et al., 1996), whether due to hypoxia (Beatty et al., 1987), alcoloholic Korsokof's Syndrome (Beaunieux et al., 1998), or transient global amnesia (Kazui et al., 1995), have been joined by numerous studies on sub-cortical dysfunction, whether due to cerebellar injury (Daum et al., 1993), schizophrenia (Goldberg et al., 1990; Gras Vincendon et al., 1994; Michel et al., 1998; Schmand et al., 1992), PD (Daum et al., 1995; Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988; Taylor & Saint Cyr, 1995), and HD (Saint Cyr & Taylor, 1992; Saint Cyr et al., 1988; Taylor & Saint Cyr, 1995) in concluding that the Towers of Hanoi and Toronto are sensitive to disorders of procedural learning. Additional experimental studies with pediatric populations (Fireman, 1996; Klahr, 1978; Regan, 1997; Vakil et al., 1997), healthy young normal controls (Clement, 1996; Fillbrandt, 1986, 1987; Groff, 1992; Groff & Saint Cyr, 1993; Klix & Rautenstrauch Goede, 1967; Kotovsky et al., 1985; Peretti et al., 1997; Poulin Dubois et al., 1989; Svendsen, 1991), as well as healthy elderly subjects (Trepanier, 1989; Trepanier & Saint Cyr, 1989; Vakil & Agmon Ashkenazi, 1997; Vakil, Hoffman, & Myzliek, 1998) have also confirmed this finding.

The majority of the findings of implicit or procedural processes in problem solving have been established by studies using either the Tower of Toronto or Tower of Hanoi. The Tower of Toronto was designed specifically with the intention of testing clinical populations with basal ganglia disease. The Tower of Hanoi has likewise been shown to tap the functions of various subcortical structures, such as the basal ganglia, along with the primary targets of basal ganglia outflow, such as the dorsolateral prefrontal cortex.

As noted in Chapter 1, the functional circuitry involving the basal ganglia and their cortical inputs and outputs have been implicated in models of procedural learning.

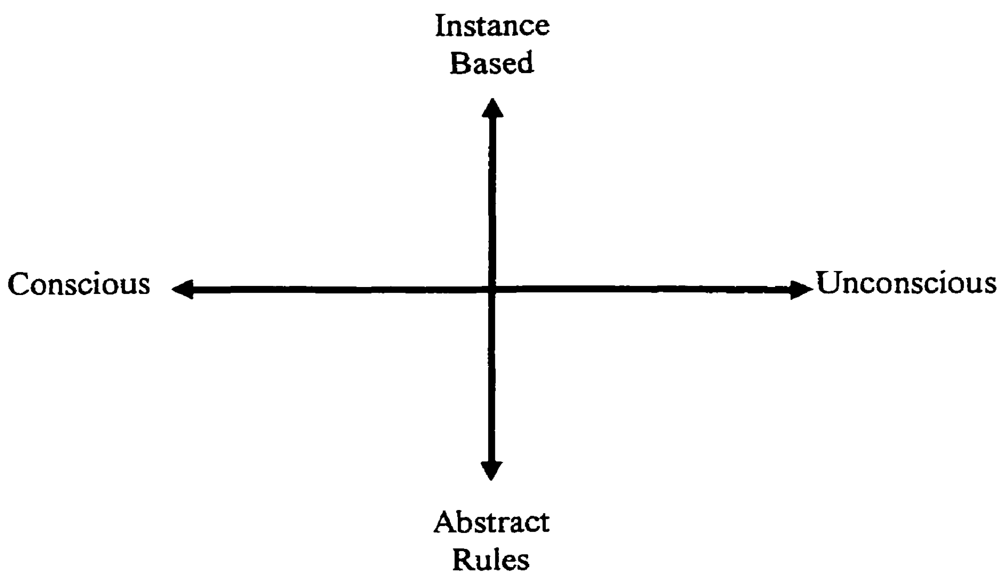
In contrast, few studies employing the Tower of London have reported similar findings. This distinction is consistent with that noted above, that the Tower of London is primarily a task which tests planning and working memory, while the Towers of Hanoi and Toronto are more complex problem solving tasks, tapping many cognitive components, including procedural learning.

Chapter 3 The Experiments

General Introduction

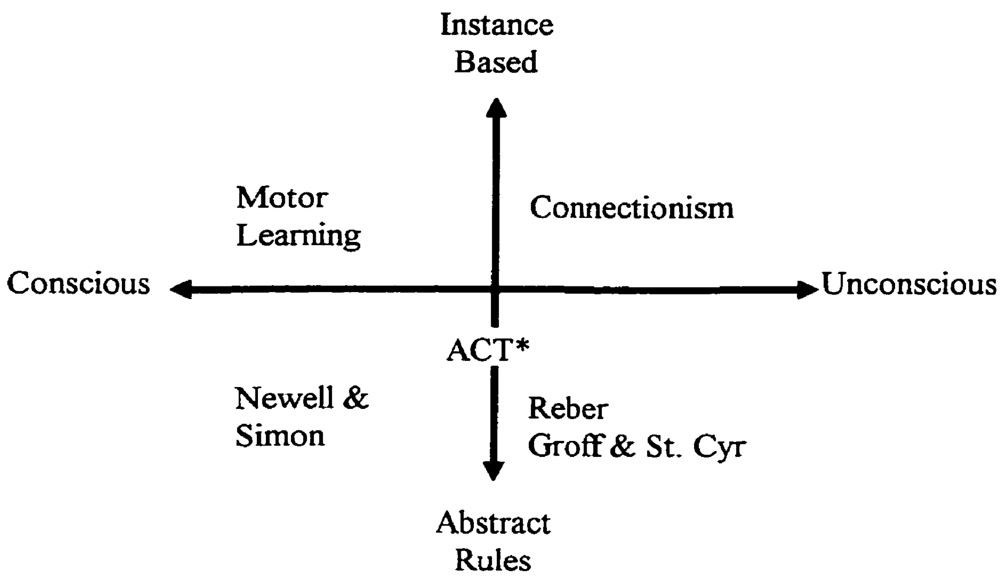
A certain amount of information has been amassed concerning the role of implicit, or procedural, learning mechanisms and the acquisition of problem solving skill on the tower. However, this view has recently come under attack. Lockhart and Blackburn (1993) argue that what is necessary to establish the existence of implicit processes in a problem solving environment is first to analyse the task, to determine to what extent conceptual access is necessary for solution. According to this view, the tower requires that subjects first make accurate "use of the concept of a 'holding' peg, rather than attempt to move the discs directly to the goal peg"(Lockhart & Blackburn, 1993 p.98). It should be noted that in his conceptual analysis of potential solution strategies, Simon (1975) only identified two out of four strategies which would require the access of this concept. Additional, empirical work in our laboratory also fails to support the notion of the goal-recursion strategy as the only possible method of solution for subjects. As has been established above, (Groff & Saint Cyr, 1993; Trepanier & Saint Cyr, 1989) many subjects, when freed from the need to verbalize a strategy during performance, default to a less efficient solution (what Trépanier calls a type four solution), which makes no use of a holding peg, at all. This would seem to negate the need for this conceptual insight for solution. On a related line of critique, Shanks and St. John (Shanks et al., 1994; 1994; Shanks & St. John, 1996) argue that the implicit processes literature is home to a conceptual confusion (on the researchers', not the subjects' part) between what is learned and how it is learned. Specifically, they argue that the concept of automaticity of learning is often conflated with the concept of abstract rules induction. Accordingly, the research to be described represents an attempt to separate these two questions, of what is learned and of how it is learned, during the acquisition of tower solving skills. A diagram (Figure 8) will best represent the separation of these two concepts: conscious versus unconscious learning, and instance learning vs. abstract rules induction.

Figure 8 The Basic Framework



In Figure 8, the ordinal axis represents the dimension of abstraction and the abscissa represents the dimension of conscious awareness. It can thus be seen that on such a co-ordinate grid it is possible to plot virtually every theory of problem solving skill acquisition. Thus Figure 9:

Figure 9 The Basic Framework: Theoretical Import



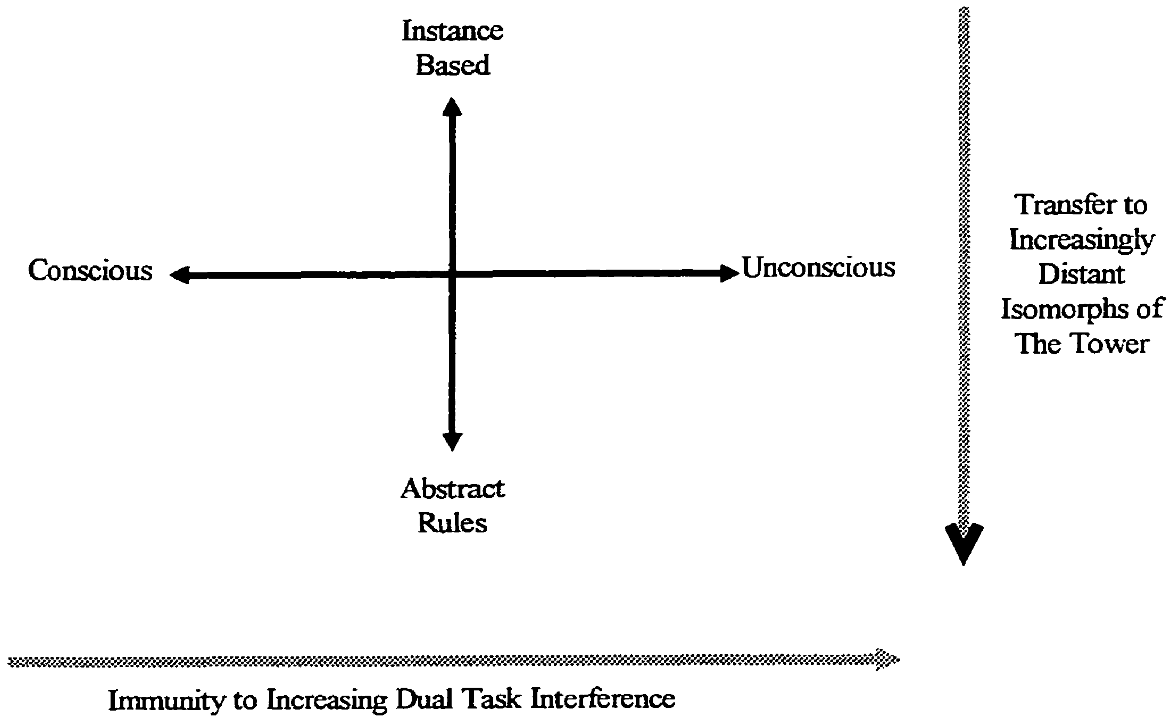
By motor learning in Figure 9, I refer not to Susan Corkin's work which I have already suggested is an example of procedural learning, but rather to classical strategy driven theories of motor skill acquisition from the kinesiology and physical education literature (See Adams, 1987 for a typical review of classical motor learning theory). Under such theories, skill learners adopt strategies of consciously refining small units of their motor behaviour until eventually a stable, overall performance goal is reached. It should be noted that such theories are limited to the early stages of learning motor skills of fine manipulation, such as typing skill. Such learning, then, encompasses both processes of conscious refinement and non-conscious proceduralization or habitualization, as described earlier in the theories of Fitts (1967), Anderson (Anderson, 1983), and for that matter, James (1890).

The connectionist literature is too vast, and varied in scope, to review here, but suffice it to say that whatever the architecture employed, the notion is always one of a distributed, and thus not declaratively available, representation of the stimulus features of an environment (See McClelland, 1988 for the classic statement of this position). The positions of Newell and Simon (1972) and of Anderson (1983) have been outline above. It can be seen that Newell and Simon's focus upon the conscious construction of rules while negotiating the state space of a problem, places them squarely in the third quadrant of the above diagram, while Anderson's ACT*, with it's emphasis upon the process of proceduralization of production rules from initial conscious hypothesis testing would place him closer to the unconscious end of the spectrum. Reber (1989), with his focus upon subjects' acquisition of the rules of grammar used to construct his letter strings, in the absence of conscious awareness, places him squarely in the fourth quadrant. Groff and Saint-Cyr, are perhaps not as adamant about this lack of awareness as Reber, and indeed concede that it is possible to solve the tower using a strategy of conscious hypothesis testing, while still maintaining that the preponderance of evidence from normal and neuropsychological data support the notion that it is also possible to solve the tower in the absence of awareness, and that indeed, in many cases, the presence of conscious awareness may actually be a hindrance (Groff & Saint Cyr, 1993).

The current studies then, represent an attempt to separately analyse the dimensions of conscious awareness during problem solving acquisition, and of the nature of what is learned during this period. It should be noted, parenthetically, that the above diagram makes use of linear representations of these dimensions and treats them as orthogonal lines. This is merely a convenience at this point, and if subsequent investigation yields a different conceptual picture, with perhaps one or both components best represented in a non-linear fashion, or with some form of interaction between the two conceptual dimensions, then the model will be revised accordingly.

The classical way of determining the extent to which a given performance is mediated by effortful, conscious processing is through the use of dual tasks to stress the system and make demands upon conscious cognitive resources (Baddeley, 1986; Hasher & Zacks, 1979; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). The more immunity to dual task interference demonstrated by acquisition of skill on the tower, the more certain we can be that the process of learning this skill is mediated by unconscious, procedural processes (Stadler & Frensch, 1998). In order to determine whether learning is instance based or involves the induction of abstract rules, a series of tests of skill transfer will be conducted. The more removed, both representationally, motorically and functionally, the isomorph to which this skill can be successfully transferred, the more abstract, and rule based, the learning must be. This is summarized in Figure 10:

Figure 10 The Basic Methodology



Method: Features Common to All Experiments

Subjects and Power

The subjects used in all three experiments were young normal controls (YNC). In general these were obtained from the Psy100 subject pool, though a few additional subjects were recruited from the friends of such students. Compensation for participation for those students enrolled in Psy100 was in the form of course credit while those not enrolled received $5.00 payment for each full or part hour of their time.

A rough calculation of a priori power was conducted for these experiments. Assuming a reasonably robust effect for both manipulations of distance of transfer and level of interference, we used Cohen's suggested ϕ' of 0.40. Having selected a β value of lower than 0.20 (0.17 from the table), we arrive at a rough calculation (for an initial df_e of ∞) of 1.6 for ϕ. The number of subjects needed in each level of treatment can thus be calculated using the formula $n = \phi^2/\phi'^2$, yielding a result of 16. In short, for each of the levels of treatment in each experiment it was decided to use 16 subjects, for a total of 64 subjects in each experiment. It should be noted that these power calculations refer only to the experimental manipulations being carried out between subjects. No attempt was made to calculate prospective power for the learning curves across trials but within subjects, due to the complexity of the issue, and their presumed robust natures. It should be noted that clear learning curves for both movements and latencies have previously been demonstrated with as few as 16 subjects in total (Groff, 1992), and indeed for movements alone with only 10 subjects per group (Trepanier, 1989).

The Tower of Toronto

The presentation of the Tower of Toronto followed conventional guidelines during training sessions (Groff & Saint Cyr, 1993; Saint Cyr et al., 1988). The traditional three practice trials on the three-disk problem given to patients prior to testing on the four-disk puzzle were omitted. Instead, calibration and practice with the tower interface was immediately followed by two sets of five trials (TT1 and TT2) on the four-disk problem with approximately 1½ hour break between TT1 and TT2.

The Tower was administered via computer using a program developed by Dr. Saint-Cyr and written by Dr. Peter Davies, which was piloted by Groff and Saint-Cyr (1993). The subjects manipulated the disks "manually" using the computer's number keypad, with the three lowest keys (numbers 1-3) representing the three pegs of the Tower. Prior to the practice trials, subjects were permitted free practice using the keypad, and a display of a single, neutral coloured disk. This free rehearsal served the purpose of familiarising the subjects with the operation of the Tower interface. Subjects then engaged in a series of trials using neutral coloured disks in which they were instructed to move the disks as quickly as possible from peg to peg. During this procedure the program recorded move latencies from each peg to every other peg when presumably no problem solving or conscious hypothesis testing were being undertaken. These calibration trials terminated after ten of each possible move had been made. A measure of median raw move time for each combination of pegs/direction and for each subject was thus determined. This motor time was subtracted from the response times of subjects during the tower test.

The program automatically records subjects' moves, plots them on the state space of the problem, records move latencies (both inter-move latencies and move times) and calculates which of Trépanier's four solution pathways the subjects used on each trial. It defaults to pathway number five if subjects fail to solve the puzzle within a ceiling of 50 moves. The program did not permit illegal moves but did record the attempt to make them, as the number of errors per trial.

The Ancillary Tests

With the exception of the PASAT, each of the following tests was performed in the interval between TT1 and TT2 on all three experiments. It was anticipated that correlations between various measures on the Tower of Toronto and these established tests of neuropsychological functions would provide additional insight into the neurocognitive processes tapped by this task.

AMNART (Grober & Sliwinski, 1991)

The American revised version of the Nelson Adult Reading Test. Subjects were asked to pronounce a list of fifty irregular words of increasing obscurity as a short estimate of verbal I.Q. Verbal I.Q. is calculated as 118.2 - .89 (no. of errors) + .64 (years of education). Correlations with the AMNART would provide an indication of the impact of general ability on this problem solving task.

Petrides Conditional Associative Learning Task (CALT)(Petrides, 1985)

An array of four disks was presented to the subject with a set of four identical cards (Petrides originally used six, the current version was developed as an easier isomorph). The subjects' task was to learn the association between the disks and the cards. The examiner tapped one of the disks and the subject responded by tapping one of the cards. The subject was told whether they chose the correct card or not. If they chose incorrectly, they were allowed to select another card (up to three by which time the only remaining card must be the associate).

The score for this test is the number of trials to criterion of correctly identifying the associated disk-card pairs, three times. The number of erroneous guesses on each trial is also recorded. This task tests the subject's directed attention and associative learning using visual-spatial stimuli. As the Tower is also a visual-spatial learning task, it was anticipated that the CALT would correlate with it, to the extent that directed attention was necessary for solving the puzzle.

Wisconsin Card Sorting Test (WCST) (Heaton, 1981)

Subjects were presented four key cards and a deck of other cards. The subjects were told to match the cards from the deck one at a time to the key cards following whatever criterion they felt appropriate. The examiner advised the subjects as to whether they were correct or incorrect after each card. At the start the experimenter answers "correct" each time the subject sorted by colour, and "incorrect" otherwise. Following ten consecutive correct sorts the examiner switched his criterion (without informing the subject) to form, and after ten correct sorts by form, to number. The process was repeated until the deck of 128 cards was depleted. The examiner recorded each response.

This task has been shown to be particularly sensitive to frontal lobe function,(Milner, 1963) and a measure of subjects' ability to generate and maintain sets. There has been evidence that the problem solving abilities tapped by the card sorting test might also be tapped by the Tower (Groff & Saint Cyr, 1993; Saint Cyr et al., 1988).

Paced Auditory Serial Addition Test (PASAT) (Gronwall & Sampson, 1974)

The subject was asked to listen to a tape recording on which numbers are heard at regular intervals. The subject was asked to add together the last two numbers heard and respond accordingly. Each response was recorded and the number of errors for each set was also recorded. The first set was presented at a rate of one digit every 2.4s, the second set at the rate of one digit every 2.0s then 1.6s and finally 1.2s. This task is designed to test attention in a time constrained setting. Again it was assumed that the degree to which focussed attention was necessary for the solution of the task, the subjects' scores on the PASAT would correlate with their performance on the Tower.

Digit Span (Wechsler, 1981)

The digit span sub-test of the WAIS-R . The examiner recited a list of digits for the subject beginning with a series of 3 digits. The subject was told they must repeat the series back. After each pair, the length of the series was increased by one. Each series was unique, with no repetition of patterns. Two consecutive failures at a given length terminated the test and the highest span length attained was recorded as the subject's digit span. After the subject's forward span was determined the task was repeated with the subject having to repeat back the sequence in reverse order, until a backwards span was similarly obtained. This task tests for attention and is an index of the subject's potential for forward and backward chaining of events. The ability to plan sequences of moves and then retain them in working memory is an explicit feature of the model of performance on the Tower of London (TOL). Including these measures of short term memory, allowed for an assessment of the similarity of processes employed by the TOL with the Tower of Toronto.

Spatial Span (Kaplan, Fein, Morris, & Delis, 1991; Milner, 1971)

A task measuring a subject's visual-spatial span. The experimenter tapped a sequence of blocks and the subject was asked to repeat the sequence. The remainder of the procedure was conducted as for the Digit Span task above. The apparatus employed was the ten block board and span lists supplied in the WAIS-R as a Neuropsychological Instrument kit (Kaplan et al., 1991). As the Tower is a visual spatial task, it was anticipated that the spatial span would be an even more sensitive measure of the role of working memory in this task than the digit span, above.

Experiment 1—Transfer of Training

Introduction

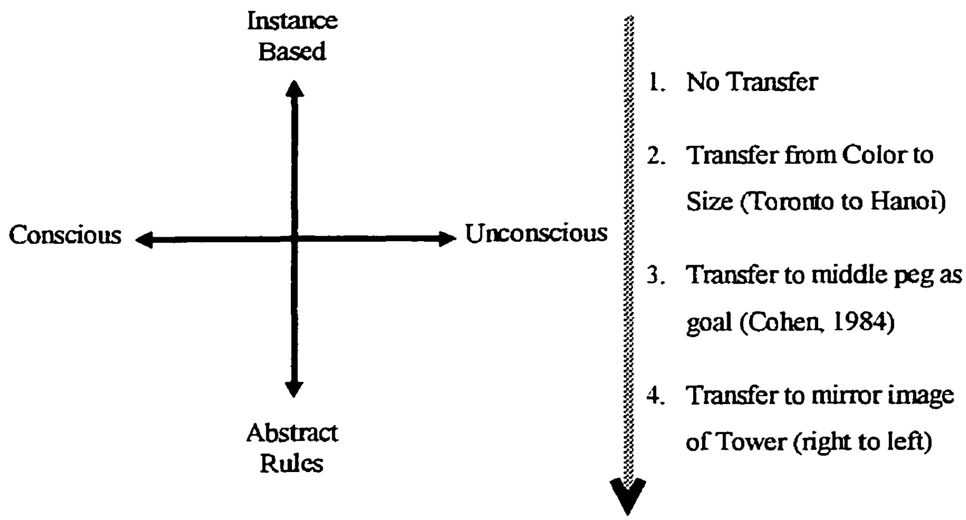
The first experiment involved testing for the transfer of problem solving skills for subjects who had been trained for ten trials on the Tower of Toronto. The issue of transfer of problem solving skills on a tower task (in contrast to analogical reasoning studies) has not been well investigated. Cohen (1984) did find that amnestic patients trained on a normal version of the Tower of Hanoi, showed savings when tested on a variant, in which the goal peg was the middle and not the rightmost peg. These results are considered somewhat tenuous, because an attempted replication found there to be no transfer (Butters & et al., 1985). This non-replication, famous though it is, should probably be treated with as much scepticism as the original result, as Butters' et al. made use of patients suffering from advanced Huntingdon's Disease, as well as patients with alcoholic Korsokoff's syndrome. As both patient groups are susceptible to quite diffuse damage, and are often hard to evaluate neuropsychologically, it is doubtful that much could be gained from such a study for a general theory of transfer in problem solving. Kenneth Kotovsky, the author of many isomorphs of the Tower of Hanoi, has made an attempt to test for transfer of problem solving skill in a population of young normal control subjects (Kotovsky & Fallside, 1989). Using two variations of his Monster/Globe Move problems, Kotovsky found that the transfer of skill, as evidenced by savings in initial learning time on the second task, was most pronounced when the transfer was taking place between tasks which were representationally similar (ie. with similar move operators) regardless of the puzzle's surface features. The proposed study is an attempt to extend Kotovsky's findings directly to the Tower of Toronto, and to attempt to find where along a gradient of dissimilarity significant transfer will no longer be present.

After completing training on the first ten trials of the 4 disk Tower of Toronto (TT1 and TT2), subjects were assigned to one of four transfer conditions, reflecting increasing levels of dissimilarity. They then performed five trials (TT3) on this transfer task. The selection of the number of levels of effect in both experiments one and two was a compromise between the well established principle that when testing random effects variables in a domain in which one is uncertain of the natural cut-points, one should sample as widely and frequently as possible, balanced against the logistics concerning the number of subjects required for each level (see power analysis above).

The first group, no transfer, involved the subjects merely performing additional five trials of performance on the 4 disk Tower of Toronto. The second group, who was transferring across a minimal distance, performed five trials on a size-coded version of the tower, i.e. a classic 4 disk Tower of Hanoi, this group then has the surface features of the tower changed but the motoric and representational features remain constant. The third group performed five trials using a transfer task similar to Neil Cohen's (1984), in that they had to solve the Tower of Toronto, with the final goal being a complete stack on the middle peg. While at first this seems quite dissimilar from the normal presentation of the tower, it must be remembered that the move operators are all still in the same direction, and indeed many sequences of moves can be reused, merely substituting destination pegs for each sequence. Thus this third transfer task is still at least partially amenable to preserved learning of instances, however the representational features are quite dissimilar as the required moves to solution are now in the third corner of the problem state space.

The fourth group had to perform five trials of the 4 disk Tower of Toronto, proceeding from the rightmost peg to the left, in short solving the initial puzzle in reverse. This fourth group then has the deep structure (the representational features) held constant while the surface and motoric features are completely reversed. It should be noted that either group three or four could be thought of as performing the more difficult transfer depending upon whether one thought the learning to be preserved was primarily motoric or representational. In either case, it was to be hoped that for either the third or fourth group (or both), instance learning should have broken down. See Figure 11 for a summary.

Figure 11 The Transfer Tasks



It was predicted that the most significant transfer would be found in the first two groups, but that significant preservation of learning would be found in the movement latencies on even the last two transfer tasks. Complete transfer of learning, regardless of the distance of the isomorph for trials 11-15, would lend strong support to the idea that what is learned on a problem-solving task, such as the tower, is some form of abstract, rule-based knowledge.

Method

Subjects

The participants for this study were 64 young normal controls (YNC), the majority of whom were recruited from an undergraduate psychology class at the University of Toronto. The average age of participants was 21.4 years (s.d. 5.4), while the average educational level was 14.5 years (s.d. 1.6). Participants displayed a wide range of familiarity with computers with average years of computer use being 5.9 (s.d. 4.2). Full descriptive statistics are presented below in Table 1. The students received course credit for participation in the study.

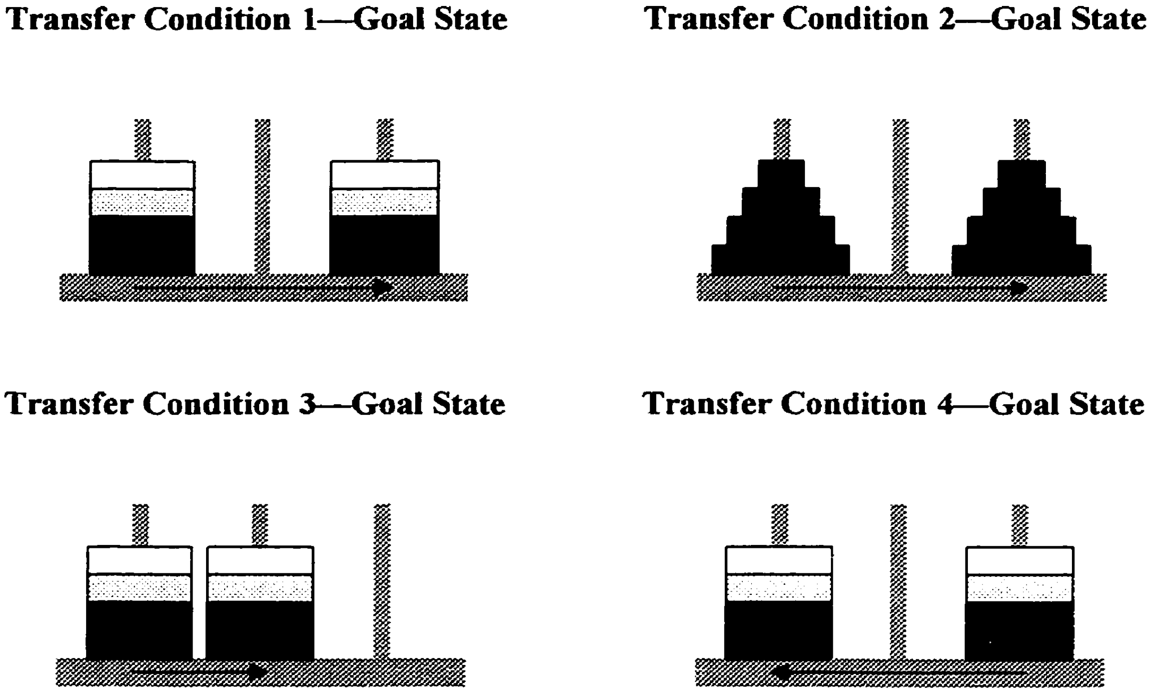
Procedure

Participants were tested in a single session of approximately 2 hours length in the Cognitive Neuropsychology Laboratory at Toronto Western Hospital. Personal information was taken (Name, Age, etc.) and consent forms signed. A throw of a single four-sided die was used to randomly assign subjects to one of four transfer conditions (rerolling as necessary once a category was filled with 16 subjects). Following this, they were introduced to the computer keyboard and invited to participate in free practice of single disk movement. The participants then participated in the first set of 5 trials on the four-disk problem of the Tower of Toronto. They were then administered a battery of ancillary psychometric tests for 1½ hour's duration. These tests served the dual purpose of further validating the clinical utility of the tower and as distracters for the participants during the gap between the first and second block of trials, inhibiting free rehearsal of solution strategies. The participants then performed the second set of 5 trials of the four-disk problem. Subjects were then given instructions for the final set of 5 trials, the transfer task. They performed 5 trials of their assigned transfer task (see below). Following the final trial, they were asked a series of questions to probe their declarative knowledge of the Tower's state space and solution strategies. Finally they were debriefed, thanked for their participation and compensated for their time.

The Tower of Toronto

The presentation of the Tower of Toronto consisted of three sets of five trials (TT1, TT2, and TT3) on the four-disk problem with 1½-hour break between TT1 and TT2. For TT3, subjects were assigned to one of four possible transfer tasks: 1) five more trials of the regular Tower of Toronto, 2) five trials with the disks arranged by size from largest to smallest, the classic Tower of Hanoi, 3) five trials of the Tower of Toronto, but with instructions to solve the puzzle with peg 2 rather than peg 3 as the goal, or 4) five trials of the Tower of Toronto with instructions to solve the puzzle in reverse, with peg 3 as the start-peg and peg 1 ad the goal-peg. These goal positions of these four transfer tasks are represented in Figure 12.

Figure 12 The Four Transfer Conditions for TT3



On all trials, the program automatically recorded subjects' moves, plotted them on the state space of the problem, recorded move latencies (both inter-move latencies and move times) and calculated which of Trépanier's (Trepanier, 1989) four solution pathways (as well as the 5th discussed above) the subjects used on each trial.

The Ancillary Tests

AMNART
Petrides Conditional Associative Learning Task (CALT)
Wisconsin Card Sorting Test (WCST)
Paced Auditory Serial Addition Test (PASAT)
Digit Span
Corsi Blocks/Spatial Span

Results

Descriptive Statistics

Descriptive statistics for this sample are presented in Table 1. The entries are the subjects' ages, education and computer experience in years, their error score on the AMNART, their verbal IQ as estimated from the AMNART, their digit and spatial spans both forward and backward, the number of errors on the CALT, and the number of trials to criterion on that task, their score on the PASAT for all four stimulus intervals, and both the number of categories and number of perseverative errors made on the WCST.

Table 1 Descriptive Statistics for Experiment 1 Sample

Measure	Mean	Minimum	Maximum	Std. Deviation
Age	21.4	17	49	5.4
Education	14.5	12	19	1.6
Computer Experience	5.9	0	20	4.2
AMNART	15.1	2	38	7.7
Verbal IQ (AMNART)	114.1	93.6	126.0	7.1
Digits Forward	10.1	6	16	2.4
Digits Backwd.	7.5	4	16	2.3
Spatial Span Forward	8.5	4	12	1.9
Spatial Span Backward	7.9	4	12	1.8
CALT Errors	8	1	51	7.5
CALT Trials to Criterion	35.1	13	113	20.2
PASAT 2.4s	41.2	8	60	12.8
PASAT 2.0s	36.6	6	59	10.9
PASAT 1.6s	28.9	8	52	10.2
PASAT 1.2s	22.4	1	51	8.7
WCST Catagories	8.5	2	11	2.1
WCST Perseverative Errors	16.1	2	50	9.5

The Learning Curves

The learning curve for moves to solution by trial is presented in Figure 13 below.[1] For the present we are not addressing the impact of the experimental manipulation and thus for all the learning curves in this section, the performance of all our subjects are represented on a single line of mean response. The error bars represent a 95% confidence interval on the mean response at each trial, and were constructed from the standard errors on the means. As can be seen the overall learning curve for moves to solution shows a fairly uniform decrease over the 15 trials of the task. Unlike previous studies (Groff & Saint Cyr, 1993) there is no increase in the moves to solution visible across the 1½ hour interval between TT1 and TT2.

---

[1] A note on axes. The ordinate was scaled from 15 (the minimum number of moves to solution on the task) to 55 (the point at which the computer program would time out, and thus the maximum number of moves to solution). This choice of axes has several advantages:

It encompasses the whole range of data, excluding no cases. Even though means and standard errors are being reported, it is considered desirable to allow for the presence of all individual scores within the range of a plot.

It provides a common frame of reference for all the plots of moves to solution (including those on primary path, below). Thus any two graphs can be conveniently overlaid or set side by side to provide direct comparisons.

It provides a common metric for all effect sizes, large or small, again allowing for ready comparison both within and between experiments.

Similar decisions were made in scaling the axes for mean of median move latencies, and for the number of events off of primary path (loops, long backtracks, and short backtracks). In each case, consistency of scale and comparability within and across studies was of primary consideration.

Figure 13 Moves to Solution by Trial

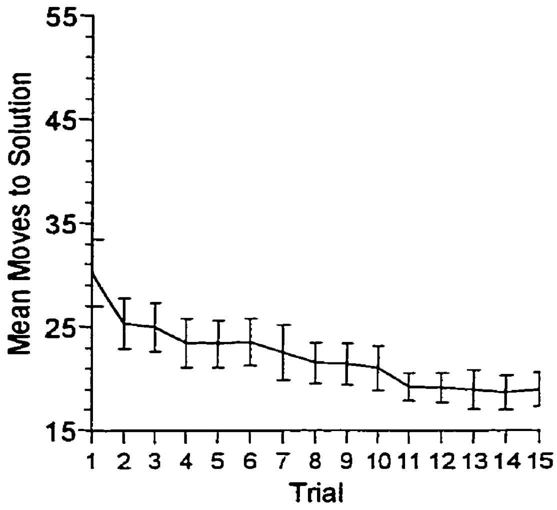
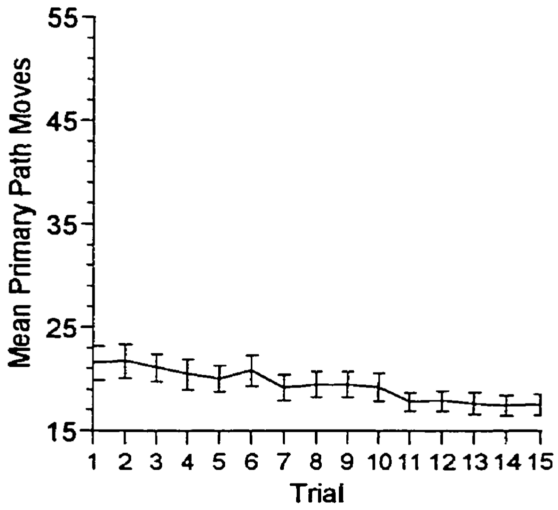


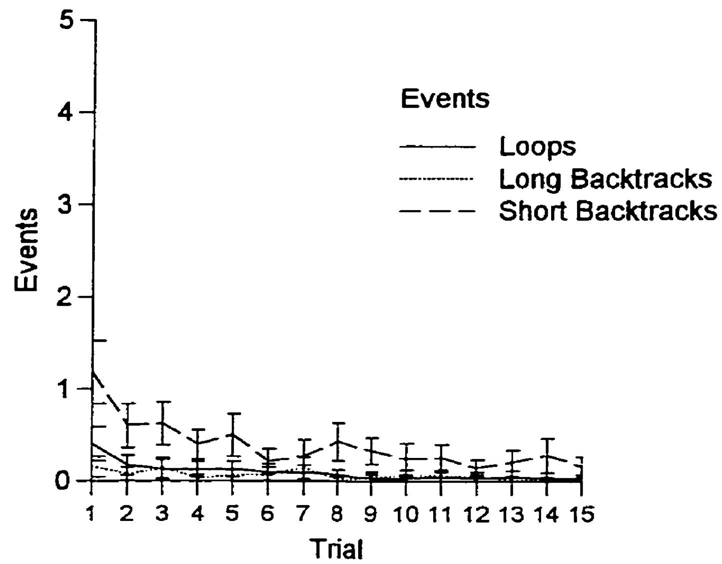
Figure 14 presents the same learning curve, but in this case using only moves that were made on primary path to solution, in other words with all loops and backtracks removed.

Figure 14 Moves on Primary Path by Trial



As can been seen from Figure 14, once loops and backtracks are removed from the measure of subjects' moves to solution, nearly all evidence of learning disappears. The sole exception being the generally decreased moves in TT3 compared to TT1 and TT2.

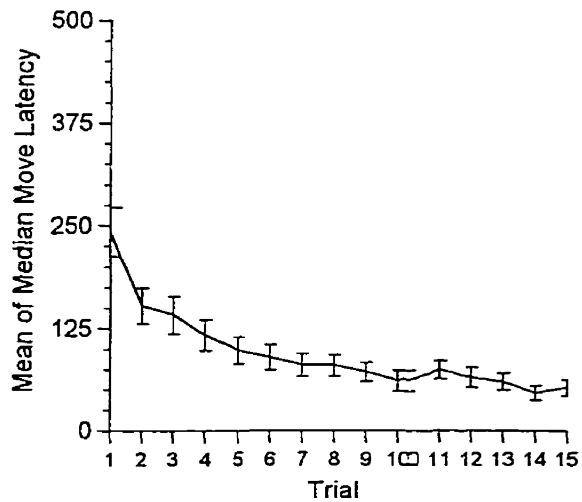
Figure 15 Loops, Long Backtracks and Short Backtracks by Trial



In order to further investigate the notion that the majority of the learning curve for moves to solution is attributable to a decrease in loops and backtracks over time, separate charts of the frequencies of loops, long backtracks (>6 moves) and short backtracks (≤6 moves) were constructed. These are presented in Figure 15. As can be seen, the majority of the decrease seen in moves to solution by trial is due to a reduction in the number of short backtracks made by subjects.

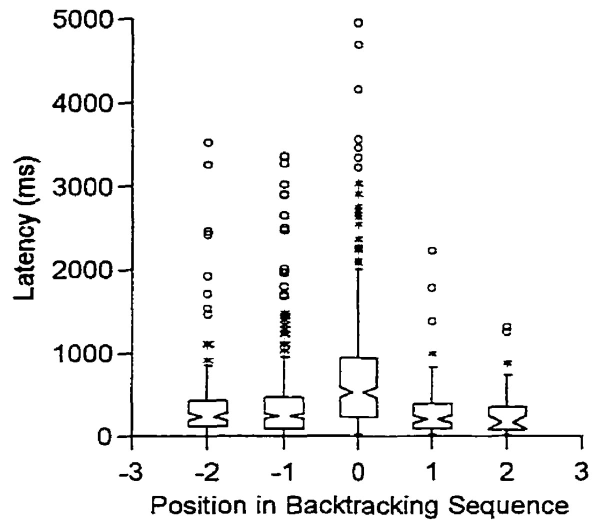
Finally, a learning curve was constructed of the mean of subjects' median move latencies across trial and presented in Figure 16. With the exception of a slight increase in median latencies on Trial 11 (the first of the transfer trials) this curve also shows a smooth decline across trials, in keeping with previous research (Groff & Saint Cyr, 1993).

Figure 16 Median Move Latency by Trial



To investigate the nature of backtracking sequences, as described in the section on moves to solution above, a plot was constructed of the average move latencies at each stage of a short backtracking event. The results are presented in Figure 17 below, which is a notched box-plot, the notches corresponding to the 95% confidence intervals on the means.

Figure 17 Notched Box-Plots of Move Latencies by Backtracking Position



The Experimental Manipulation

A split-plots factorial analysis of variance (ANOVA) was conducted with transfer condition as the between-subjects effect and trial as the within-subjects effect, on the dependent variable, mean number of moves to solution. The results are summarised in Table 2 below.

Table 2 ANOVA for Mean Moves to Solution

Source	SS	df	MS	*F*	*p*	$p_{adjusted}$ Greenhouse-Geiser	$p_{adjusted}$ Huynh-Feldt
Condition	500.758	3	166.919	0.390	0.760		
Subjects(Condition)	25668.958	60	427.816				
Trial	9020.827	14	644.345	13.465	<0.001	<0.001	<0.001
Trial x Condition	2830.023	42	67.381	1.408	0.047	0.093	0.074
Trial x Subjects(Condition)	40195.417	840	47.852				

Greenhouse-Geisser Epsilon: 0.5866 Huynh-Feldt Epsilon: 0.7222
Effect Size (Condition): *r=0.095* Counternull (Condition): 0.19

As can be seen there is a significant effect for trial, but no others, particularly once the within-subjects effects are adjusted for departures from sphericity, and inflated family-wise and experiment-wise error rates are taken into account.

A similar split-plots factorial analysis of variance (ANOVA) was conducted with transfer condition as the between-subjects effect and trial as the within-subjects effect, on the dependent variable, median move latencies. The results are summarised in Table 3 below.

Table 3 ANOVA for Median Move Latencies

Source	SS	df	MS	F	p	$p_{adjusted}$ Greenhouse-Geiser	$p_{adjusted}$ Huynh-Feldt
Condition	186815.5	3	62271.8	1.58	0.204		
Subjects(Condition)	2365363.9	60	39422.7				
Trial	3899814.3	14	278558.2	72.022	<0.001	<0.001	<0.001
Trial x Condition	110550.2	42	2632.2	0.681	0.940	0.660	0.672
Trial x Subjects(Condition)	3248834.9	840	3867.6				

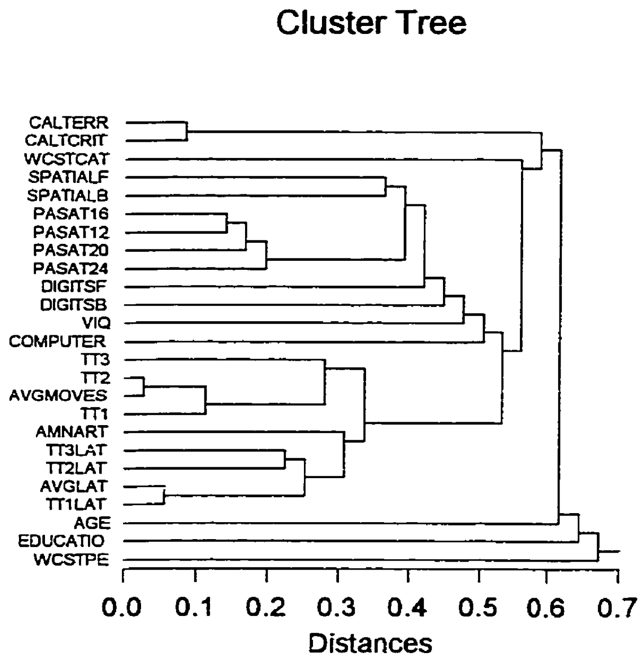
Greenhouse-Geisser Epsilon: 0.1373 Huynh-Feldt Epsilon: 0.1488

Again there is a significant effect of trial, as would be expected from the learning curve above, and no other factors even approach significance.

The Ancillary Tests

To investigate the role of individual differences in the solution of the Tower, analyses were conducted comparing the results of the ancillary tests to measures of both moves to solution and move latency, both broken down by the segment of testing (TT1, TT2, TT3) and overall. The variables were entered into a hierarchical cluster analysis algorithm,using a centroid linkage method and a Pearson's r distance metric. The results are presented graphically in the following dendrogram, Figure 18. The length of the horizontal lines represent the distances between centroids of clusters and the axis is calibrated as 1-Pearson's r.

Figure 18 Dendrogram for Experiment 1.



As can be seen, while one could divide the ancillary tests up into a number of different clusters, depending on the distance one wished to consider sufficiently large, the Tower measures all form a relatively homogenous, and independent cluster, on their own. The only exception is the relatively strong association between the number of errors subjects made on the AMNART and the latency measures for the Tower.

Discussion of Results

As noted in the introduction to this experiment, it was anticipated that there would be significant preservation of learning in even the most extreme transfer conditions. The above results have actually gone considerably further than this. The inability to nullify the hypothesis that degree of transfer had no impact on subjects performance on trials 11-15 is quite remarkable. While it is, of course, impossible to "prove" a null hypothesis, this finding is in the expected direction, and quite solid, for a number of reasons. First there was the a priori power analysis which concluded that Power of 0.83 would be obtained with a sample of this size. Second, there is the fact that the a posteriori effect size obtained for degree of transfer on moves to solution is quite small (r=0.095). Finally, even the counternull effect size, that effect size that is equiprobable to the null effect size is also quite small ($r_{\text{counternull}} = 0.19$).

Thus the primary finding of Experiment 1 is that the learning on the Tower of Toronto is quite robust, even when transfering to problems that differ in terms of the problem's state space (Condition 3) or its perceptual motor features (Condition 4). Few neuropsychological tests show such robustness (Lezak, 1995), and the results suggest that it should be possible to easily create alternate forms of this test for repeated use in conditions such as pre/post surgical trials, or neuroimaging studies.

Experiment 2—Learning Under Interference

Introduction

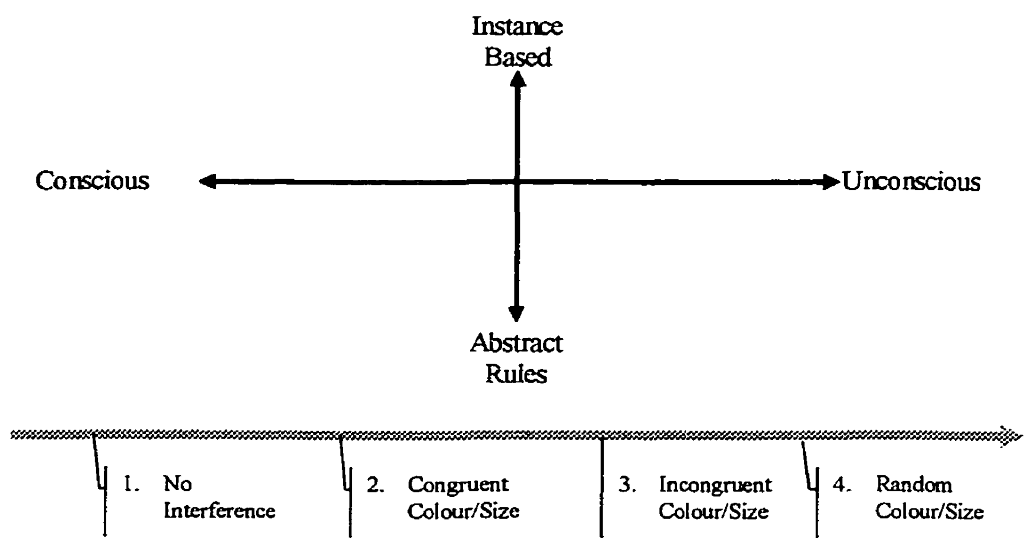
As yet, there is not an extensive literature on the systematic effects of dual task interference on the acquisition of a skill for solving problems like the Tower. Dual task interference has been investigated in only one study with the Tower of London. While verbal and visual-spatial executive tasks interfered with TOL performance, articulatory suppression facilitated performance. The authors interpret these results as evidence of executive verbal and spatial components sub-serving this task, though they question the possibility of a role for verbally mediated preplanning (Phillips et al., 1999).

Accordingly, in designing this paradigm I have taken as my guide the work of Baddeley (See 1986 for his clearest statement) and others following in his tradition. I am assuming that dual task interference of a puzzle, such as the Tower, would primarily be due to an overloading of the visual-spatial sketchpad, and have designed my levels of interference accordingly. In Baddeley's paradigms, subjects are required to perform tasks while simultaneously performing secondary, distracter tasks which are believed to use up cognitive resources, and allow for only unconscious processes to work on the primary tasks. By varying the similarity of modality and operations of the secondary task to the primary tasks, it is believed that greater or fewer resources of working memory will be available to accomplish the primary task in a conscious fashion. Thus, by examining the degree to which a given primary task is immune to such interference, it should be possible to ascertain how conscious a task it normally is.

Due to the difficulty of engineering a second visual-spatial problem-solving task that subjects could engage in, while solving the Tower on the computer, an alternative to strict dual task interference was sought. Turning to the literature on the Stroop effect, it was thought that it might be possible to develop different levels of interference that could be incorporated directly into the Tower stimuli. In the traditional Stroop task, (Stroop, 1935) interference was produced on both subjects reading of a list of words, and their identification of colours, by the simple expedient of printing colour words in one of congruent, incongruent or neutral (black) ink. Subsequent studies have found both evidence of facilitation of performance when the ink colours and colour words are congruent, and of interference when they are incongruent (See MacLeod, 1991; 1992 for extensive reviews of this literature). Interpretations of these results have ranged from the assumption that reading is such an over-learned skill that it is prepotent, and cannot be inhibited even when the primary task is the identification of ink colours, to the simple assumption of standard dual task interference, to a competition among multiple routes for processing of written materials, one phonemic and one semantic. Regardless of the interpretation presented, however, it seems to be consistently found that the presence of an extra dimension of stimulus features can either enhance or inhibit subjects' performance on a primary task. The levels of interference for subjects in this experiment were constructed with this in mind. It was decided to vary the sizes of the disks on the task, while maintaining the colours, and colour-based rules of the Tower of Toronto.

Subjects in the first interference condition, no interference, will simply learn to solve the puzzle during two sets of five trials (TT1 and TT2) with no additional stimulus features, in short the typical ten trials of the Tower of Toronto. Subjects in the second interference condition, congruence, will be presented with a Tower that is not only organised according to the rules of the Tower of Toronto, but also of the Tower of Hanoi, in other words, the coloured disks will be arranged from largest to smallest as well as darkest to lightest. Subjects in the third experimental condition, the incongruent condition, will also have disks organised by size as well as colour, however they will be organised opposite to the traditional Tower of Hanoi, with the largest disk on top and the smallest on the bottom. Finally, in the fourth, or random, interference condition, the relationship between the size and colour of each disk will be determined randomly at the start of each trial, subject to the constraint that neither the configurations for conditions two or three are possible. To summarise see Figure 19:

Figure 19 The Dual Task Interference Conditions



It was anticipated that subjects would find the solution of a size-based tower such as Hanoi, easier than that of the typical colour rules of Toronto. Condition two, was thus expected to facilitate performance, while conditions three and four were expected to interfere with performance. It was thought that the fourth condition would produce the most interference, as there would be no lawful relationship between the sizes and colours of disks for the subjects to learn from trial to trial. If the learning on the Tower were truly automatic, it should be the case that no interference effects would be found.

Method

Subjects

The participants for this study were 64 young normal controls (YNC), recruited from an undergraduate psychology class at the University of Toronto. The average age of participants was 22.6 years (s.d. 5.7), while the average educational level was 15.2 years (s.d. 2.0). Participants displayed a wide range of familiarity with computers with average years of computer use being 6 (s.d. 2.7). Full descriptive statistics are presented in Table 4 below. The students received course credit for participation in the study.

Procedure

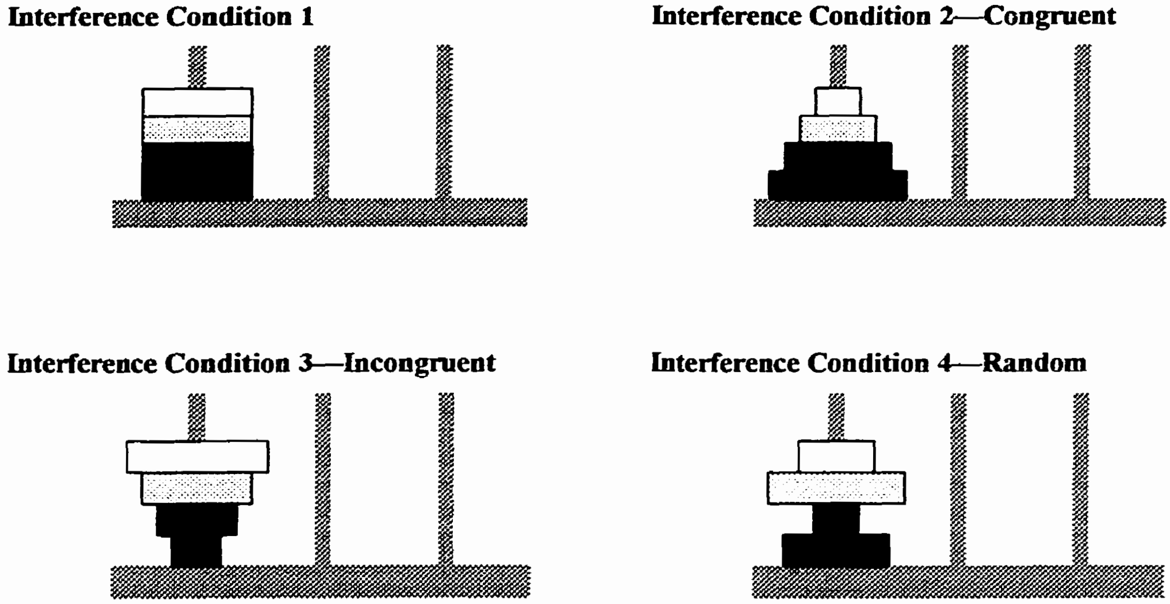
Participants were tested in a single session of approximately 2 hours length in the Cognitive Neuropsychology Lab at Toronto Western Hospital. Personal information was taken (Name, Age, etc.) and consent forms signed. Subjects were randomly assigned to one of the interference conditions using the same method described for assigning conditions in Experiment 1 above. Following this, they were introduced to the computer keyboard and invited to participate in free practice of single disk movement. The participants then participated in the first set of 5 trials on the four-disk problem of the Tower of Toronto (TT1). They were then administered a battery of ancillary psychometric tests for approximately 1½ hour's duration. These tests served the dual purpose of further validating the clinical utility of the tower and as distracters for the participants during the gap between the first and second block of trials, inhibiting free rehearsal of solution strategies. The participants then performed the second set of 5 trials of the four-disk problem. Finally they were debriefed, thanked for their participation and compensated for their time.

The Tower of Toronto

The presentation of the Tower of Toronto consisted of two sets of five trials (TT1, TT2) on the four-disk problem with 1½-hour break between TT1 and TT2. The Tower was administered via computer. The subjects manipulated the disks "manually" using the computer's number keypad, with the three lowest keys (numbers 1-3) representing the three pegs of the Tower. Prior to the practice trials, subjects were permitted free practice using the keypad, and a display of a single, neutral coloured disk. This free rehearsal served the purpose of familiarising the subjects with the operation of the Tower interface. Subjects then engaged in a series of trials using neutral coloured disks in which they were instructed to move the disks as quickly as possible from peg to peg. During this procedure the program recorded move latencies from each peg to every other peg (the practice time terminated after ten of each possible move had been made) when presumably no problem solving or conscious hypothesis testing were being undertaken. A measure of median raw move time for each combination of pegs/direction and for each subject was thus determined. This motor time was subtracted from the response times of subjects during the tower test. The program did not permit illegal moves but did record the attempt to make them.

Subjects were assigned to one of four possible interference conditions (See Figure 20): 1) The regular Tower of Toronto with no colour-size interference; 2) The congruent condition in which the disks were arranged by colour according to the Tower of Toronto, but also by size according to the classic Tower of Hanoi; 3) The incongruent condition, in which the disks were arranged according to colour and size as above, but with the size relationship reversed from the classic Tower of Hanoi—i.e. the largest disk on top and the smallest on the bottom; or 4) The random condition, in which the sizes of the disks were assigned to the colours randomly at the start of each trial with the restriction that neither the arrangements of conditions two or three could be produced. Despite the colour-size interference in which the subjects were tests, the only instructions they received concerned the colour-based rules of the Tower of Toronto. No attention was drawn to the sizes of the disks, or even to the idea that disks could be of different sizes. The computer program also only enforced the rules of the Tower of Toronto.

Figure 20 The Four Interference Conditions



On all trials, the program automatically recorded subjects' moves, plotted them on the state space of the problem, recorded move latencies (both inter-move latencies and move times) and calculated which of Trépanier's (1989) four solution pathways (as well as the 5th discussed above) the subjects used on each trial.

The Tests

AMNART
Petrides Conditional Associative Learning Task (CALT)
Wisconsin Card Sorting Test (WCST)
Paced Auditory Serial Addition Test (PASAT)
Digit Span
Corsi Blocks/Spatial Span

Results

Descriptive Statistics

Descriptive statistics for this sample are presented in Table 4. The entries are the subjects' ages, education and computer experience in years, their error score on the AMNART, their verbal IQ as estimated from the AMNART, their digit and spatial spans both forward and backward, the number of errors on the CALT, and the number of trials to criterion on that task, their score on the PASAT for all four stimulus intervals, and both the number of categories and number of perseverative errors made on the WCST.

Table 4 Descriptive Statistics for Experiment 2 Sample

Measure	Mean	Minimum	Maximum	Standard Deviation
Age	22.6	18	54	5.7
Education	15.2	12	19	2.0
Computer Experience	6.0	0	12	2.7
AMNART	19.315.1	4	42	8.2
Verbal IQ	110.8	89.8	126.2	7.7
Digits Forward	10.7	6	15	2.3
Digits Backward	7.0	2	12	2.3
Spatial Span Forward	8.8	5	12	1.8
Spatial Span Backward	8.7	5	12	1.4
CALT Errors	8.5	0	71	9.1
CALT Trials	27.1	12	68	12.1
PASAT 2.4s	44.3	22	60	9.2
PASAT 2.0s	40.4	4	59	10.8
PASAT 1.6s	33.0	5	54	10.5
PASAT 1.2s	24.3	5	47	8.4
WCST Catagories	8.2	2	11	2.0
WCST Perseverative Errors	14.1	6	44	7.9

The Learning Curves

The learning curve for moves to solution by trial is presented in Figure 21 below. The error bars represent a 95% confidence interval on the mean response at each trial, and were constructed from the standard errors on the means. As can be seen the overall learning curve for moves to solution shows a fairly uniform decrease over the 10 trials of the task. Like in previous studies (Groff & Saint Cyr, 1993) there is a visible (though not in this case significant at the .05 level) increase in the moves to solution visible across the 1½ hour interval between TT1 and TT2.

Figure 21 Mean Moves to Solution by Trial

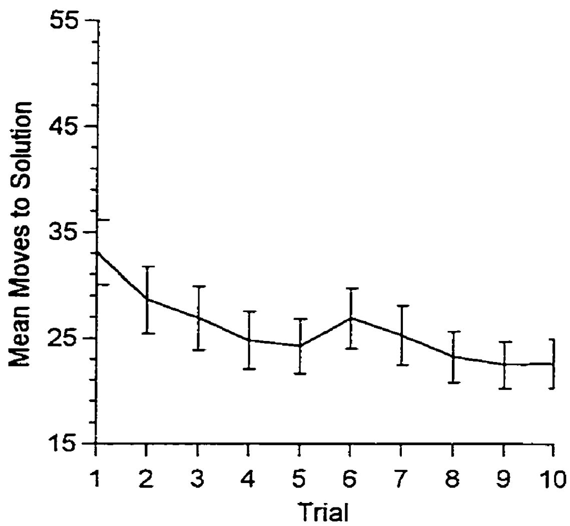
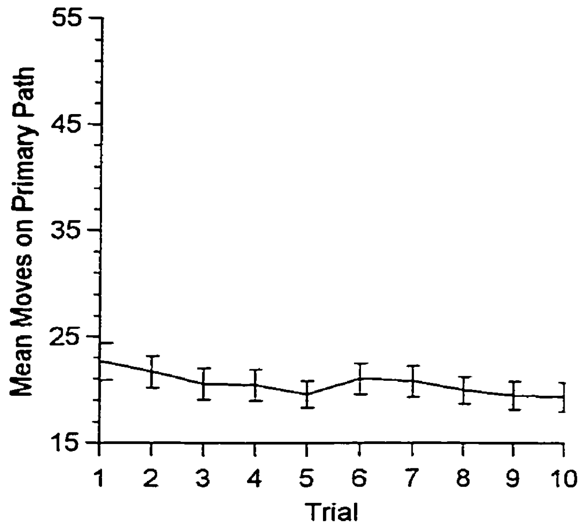


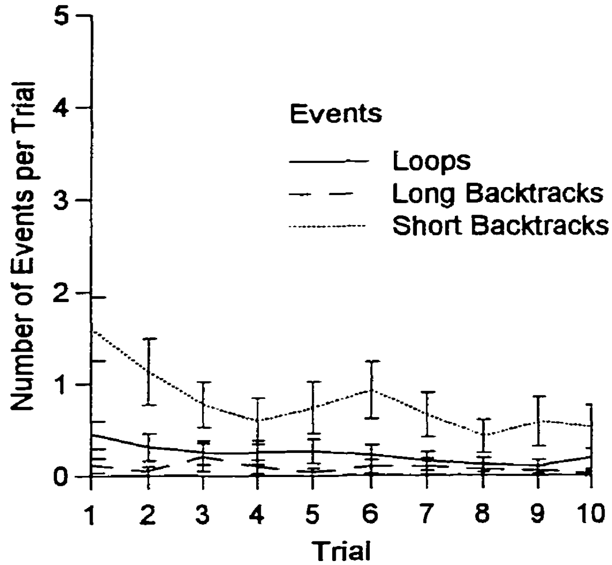
Figure 22 presents the same learning curve, but in this case using only moves that were made on primary path to solution, in other words with all loops and backtracks removed.

Figure 22 Primary Path Moves to Solution by Trial



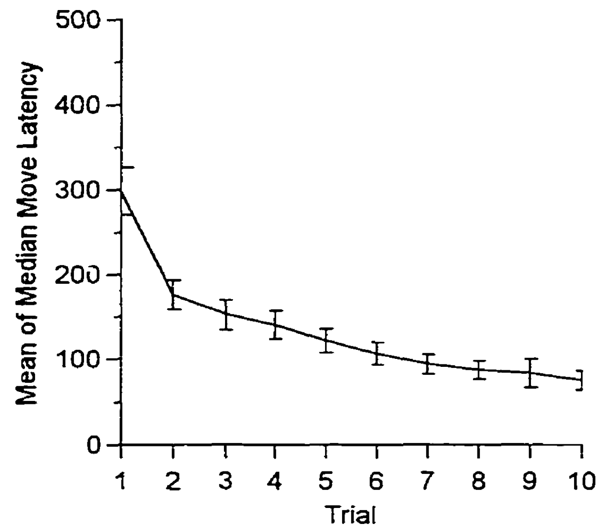
In order to further investigate the notion that the majority of the learning curve for moves to solution is attributable to a decrease in loops and backtracks over time, separate charts of the frequencies of loops, long backtracks (>6 moves) and short backtracks (≤6 moves) were constructed. These are presented in Figure 23. As can be seen, the majority of the decrease seen in moves to solution by trial is due to a reduction in the number of short backtracks made by subjects.

Figure 23 Loops, Long and Short Backtracks by Trial



Finally, a learning curve was constructed of the mean of subjects' median move latencies across trial and presented in Figure 24. With the exception of a slight increase in median latencies on Trial 6 this curve also shows a smooth decline across trials, in keeping with previous research (Groff & Saint Cyr, 1993).

Figure 24 Median Move Latencies by Trial



The Experimental Manipulation

A split-plots factorial analysis of variance (ANOVA) was conducted with interference condition as the between-subjects effect and trial as the within-subjects effect, on the dependent variable, mean number of moves to solution. The results are summarised in Table 5 below.

Table 5 ANOVA for Mean Moves to Solution

Source	SS	Df	MS	*F*	*p*	$p_{adjusted}$ Greenhouse-Geiser	$p_{adjusted}$ Huynh-Feldt
Condition	15737.9	3	512.64	1.407	0.250		
Subjects(Condition)	21867.5	60	364.46				
Trial	6370.5	9	707.84	7.484	<0.001	<0.001	<0.001
Trial x Condition	1990.2	27	73.71	0.779	0.781	0.749	0.775
Trial x Subjects(Condition)	51074.7	540	94.58				

Greenhouse-Geisser Epsilon: 0.7951 Huynh-Feldt Epsilon: 0.9587
Effect Size (Condition): *r=0.08* Counternull (Condition): 0.16

As can be seen there is a significant effect for trial, but no others, particularly once the within-subjects effects are adjusted for departures from sphericity, and inflated family-wise and experiment-wise error rates are taken into account.

A split-plots factorial analysis of variance (ANOVA) was conducted with interference condition as the between-subjects effect and trial as the within-subjects effect, on the dependent variable, median move latencies. The results are summarised in Table 6.

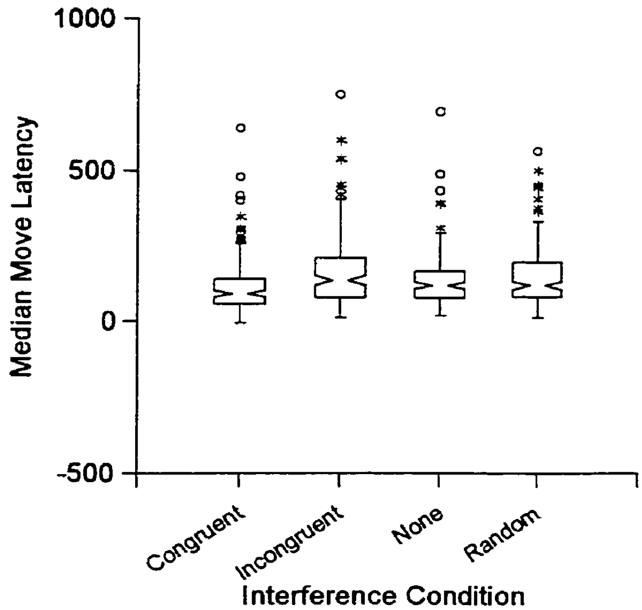
Table 6 ANOVA for Median Move Latencies

Source	SS	df	MS	*F*	*p*	$p_{adjusted}$ Greenhouse-Geiser	$p_{adjusted}$ Huynh-Feldt
Condition	189450.8	3	63180.3	2.951	0.040		
Subjects(Condition)	1284679.0	60	21411.3				
Trial	3330146.5	9	2878.9	111.379	<0.001	<0.001	<0.001
Trial x Condition	77731.5	27	2878.9	0.867	0.662	0.581	0.593
Trial x Subjects(Condition)	1793953.7	540	3322.1				

Greenhouse-Geisser Epsilon: 0.4414 Huynh-Feldt Epsilon: 0.5003

There are both significant main effects for the interference condition, as well as trial, with no significant interaction between the two. The main effect of trial is evident in the learning curve above. To explore the effect of interference condition, as set of notched box plots for median move latency, by interference condition, and is presented in Figure 25. The width of the notches is determined by a 95% confidence interval on the means, and thus these plots present the same information as would be available from post-hoc testing, without need to inflate the experiment-wise error rate. As can be seen, there is evidence that subjects' performance under conditions of congruent interference was facilitated relative to the others.

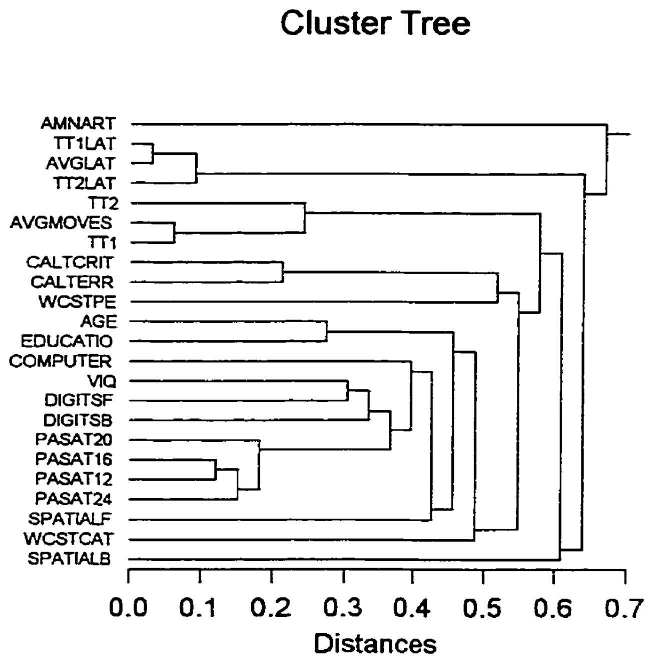
Figure 25 Median Move Latencies by Condition



The Ancillary Tests

To investigate the role of individual differences in the solution of the Tower, analyses were again conducted comparing the results of the ancillary tests to measures of both moves to solution and move latency, both broken down by the segment of testing (TT1, TT2, TT3) and overall. As in Experiment 1, all the variables were entered into a hierarchical cluster analysis algorithm, using a centroid linkage method and a Pearson's r distance metric. The results are presented graphically in the following dendrogram, Figure 26.

Figure 26 Dendrogram for Experiment 2



In the first experiment the Tower measures all formed a relatively homogenous, and independent cluster. Here, the Tower measures break fairly neatly into those measure related to moves to solution, and those related to move latencies. The former, are more closely related to the ancillary tests than the latter. The relationship seen between the AMNART and the latency measures on the first experiment has not been replicated though it remains the only test closely related to the latency measures.

Discussion of Results

There was no demonstrable impact of level of interference on the number of moves to solution taken by subjects to complete this task. As in Experiment 1, we cannot take the lack of a significant *F* for the effect of interference as proof of the lack of an effect, however we again have evidence that bolsters the idea of resistance to interference. First, we have the a priori power analysis which again suggested that with this sample size we should have power to detect a medium effect of approximately 0.83. Then again, there is the a posteriori analysis of effect sizes which in this case reveals an estimated effect size which was quite small (r=0.08) with a small associated counternull effect size ($r_{counternull}$=0.16). Thus while we can't conclude an effect size of zero for our interference manipulation, the largest effect size equiprobable to an effect size of zero is one of only 0.16.

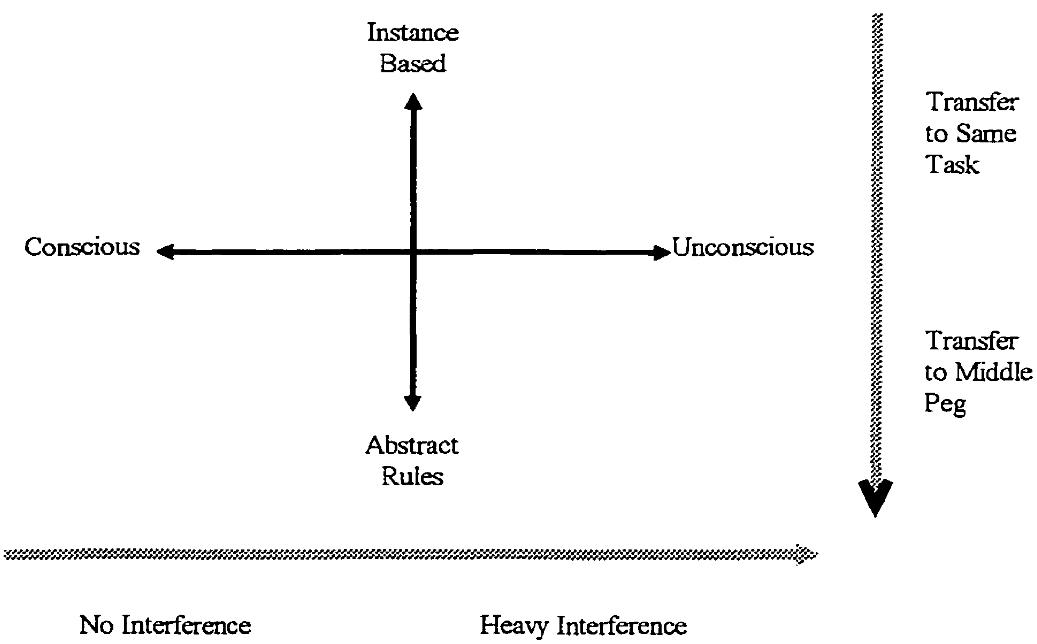
It was interesting to note that the interference manipulation was not completely without effect, however. Subjects in the congruent interference condition did perform significantly faster than those in the other three conditions. Such facilitation of move latencies is quite common with congruent conditions in Stroop interference tasks (MacLeod, 1991, 1992) and indeed was predicted prior to the experiment.

Experiment 3—Transfer After Interference

Introduction

As stated earlier, the assumption was made during the construction of the basic model that the dimension of consciousness and the dimension of abstraction were independent of one another. The third experiment consisted of an empirical test of this assumption. By testing subjects using combinations of the extremes of both interference and transfer used in Experiments 1 and 2, it was hoped that the degree of relationship between these variables would be uncovered. Accordingly, subjects were trained on ten trials of the Tower under conditions of either no interference or heavy interference, and then tested on five trials of either the same task, or a transfer task (See Figure 27).

Figure 27 The Basic Methodology



Based upon the findings of Experiments 1 and 2 it is predicted that neither the level of interference nor the difficulty of transfer will have an effect on subjects' performances.

Method

Subjects

The participants for this study were 64 young normal controls (YNC), recruited from an undergraduate psychology class at the University of Toronto. The average age of participants was 21.3 years (s.d. 5.1), while the average educational level was 14.7 years (s.d. 1.7). Participants displayed a wide range of familiarity with computers with average years of computer use being 6.7 (s.d. 3.6). Full descriptive statistics are presented in Table 7 below. The students received course credit for participation in the study.

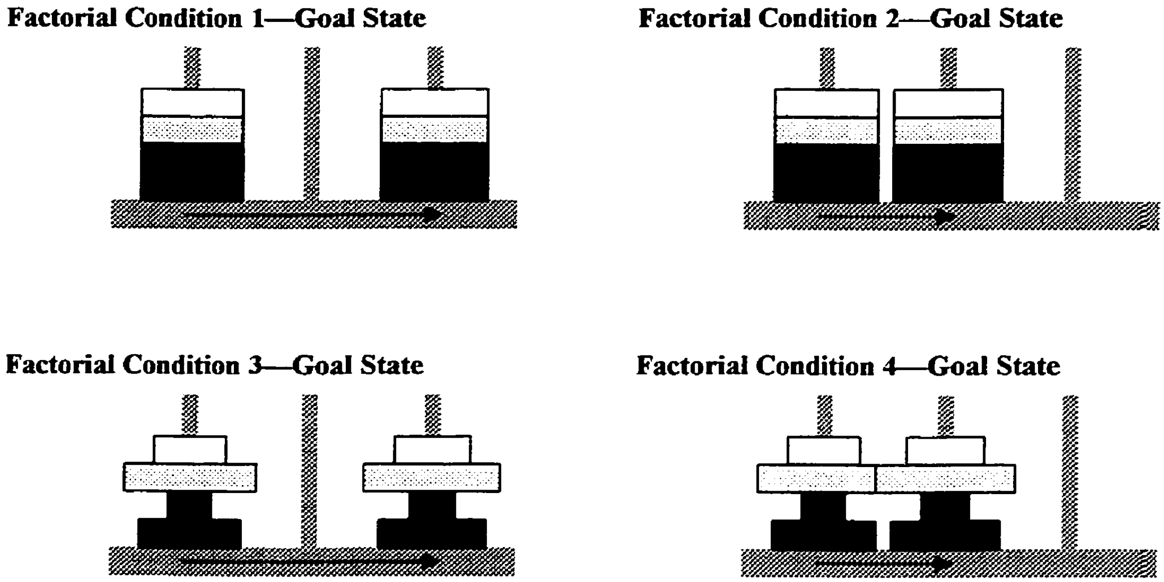
Procedure

Participants were tested in a single session of approximately 2 hours' length in the Cognitive Neuropsychology Lab at Toronto Western Hospital. Personal information was taken (Name, Age, etc.) and consent forms signed. A throw of a single four-sided die was used to randomly assign subjects to one of four experimental conditions. Following this, they were introduced to the computer keyboard and invited to participate in free practice of single disk movement. The participants then participated in the first set of 5 trials on the four-disk problem of the Tower of Toronto (TT1) under one of two interference conditions. All subjects were then administered a battery of ancillary psychometric tests for approximately one-hour duration. These tests served the dual purpose of further validating the clinical utility of the tower and as distracters for the participants during the gap between the first and second block of trials, inhibiting free rehearsal of solution strategies. The participants then performed the second set of 5 trials of the four-disk problem under the same interference conditions as before, (TT2). Subjects were then given instructions for the final set of 5 trials, the transfer task (TT3). They performed 5 trials of the transfer task (see Figure 28 below). Finally they were debriefed, thanked for their participation and compensated for their time.

The Tower of Toronto

The presentation of the Tower of Toronto consisted of three sets of five trials (TT1, TT2, and TT3) on the four-disk problem with 1-hour break between TT1 and TT2. For the first ten trials, subjects performed under one of two interference conditions. Subjects in conditions 1 and 2 performed these trials under conditions of no interference-the typical Tower of Toronto administration. Subjects in conditions 3 and 4 performed these trials under conditions of heavy colour-size interference—equivalent to the random condition in Experiment 2. For TT3, subjects were assigned to 1 of 2 possible transfer tasks. Subjects in conditions 1 and 3 simply performed five more trials of the Tower, equivalent to the no transfer condition in Experiment 1. Subjects in conditions 2 and 4 were instructed to solve the puzzle with the middle peg as the goal peg—equivalent to condition 3 in Experiment 1.

Figure 28 The Four Interference Conditions x Transfer Goal States



The Tests

AMNART
Petrides Conditional Associative Learning Task (CALT)
Wisconsin Card Sorting Test (WCST)
Digit Span
Spatial Span

Note that the PASAT was dropped from this list. This test had proven notoriously difficult to both administer and score, and provoked a great number of complaints from subjects in the first two experiments. These two facts coupled with the fact that on neither Experiment 1 or 2 did the PASAT correlate with any other tests, or Tower measures, it seemed more effort then it was worth. This did reduce the time for the interval between trials five and six somewhat, to just over one hour's duration. It was not anticipated that this would be of any consequence as there was no compelling evidence that a delay of even 1½ hours between TT1 and TT2 had any impact on subjects' performance of the task.

Results

Descriptive Statistics

Descriptive statistics for this sample are presented in Table 7. The entries are the subjects' ages, education and computer experience in years, their error score on the AMNART, their verbal IQ as estimated from the AMNART, their digit and spatial spans both forward and backward, the number of errors on the CALT, and the number of trials to criterion on that task, and both the number of categories and number of perseverative errors made on the WCST.

Table 7 Descriptive Statistics for Experiment 3 Sample

Measure	Mean	Minimum	Maximum	Standard Deviation
Age	21.3	18	44	5.1
Education	14.7	14	26	1.7
Computer Experience	6.7	1	15	3.6
AMNART	20.3	2	42	9.5
Verbal IQ	109.6	89.8	133.1	8.8
Digits Forward	11.3	6	16	2.1
Digits Backward	7.6	3	13	2.3
Spatial Span Forward	10.2	4	14	2.0
Spatial Span Backward	9.5	6	14	1.8
CALT Errors	7.5	1	29	4.9
CALT Trials	36.7	14	97	17.3
WCST Catagories	8.0	2	11	2.1
WCST Perseverative Errors	17.4	9	39	7.6

The Learning Curves

The learning curve for moves to solution by trial is presented in Figure 29 below. The error bars represent a 95% confidence interval on the mean response at each trial, and were constructed from the standard errors on the means. As can be seen the overall learning curve for moves to solution shows a fairly uniform decrease over the 15 trials of the task. Again, like in Experiment 1 there is no increase in the moves to solution visible across the 1½ hour interval between TT1 and TT2.

Figure 29 Mean Moves to Solution by Trial

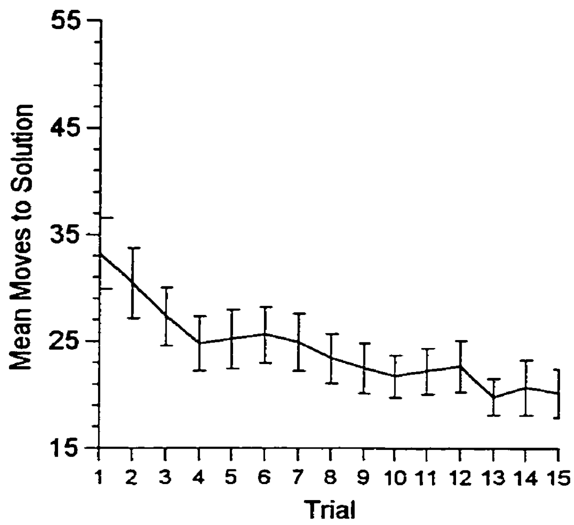
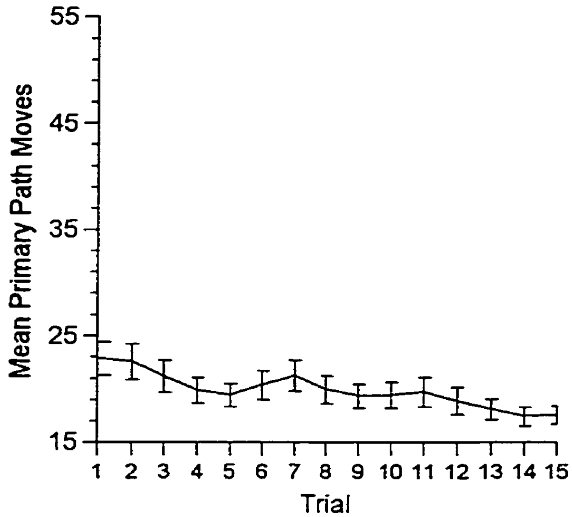


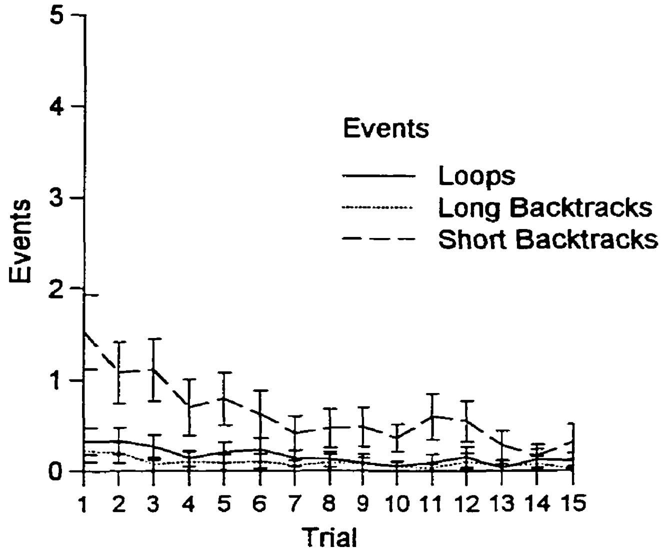
Figure 30 presents the same learning curve, again using only moves that were made on primary path to solution, in other words with all loops and backtracks removed. The primary path shows a relatively flat learning curve, as in the previous two studies.

Figure 30 Primary Path Moves by Trial



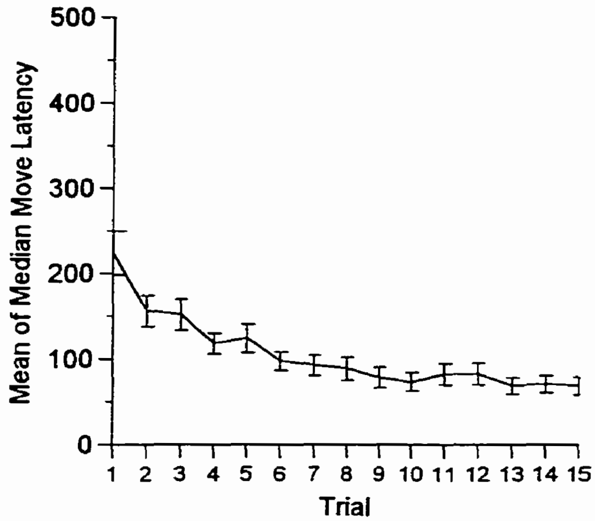
As in the previous studies, to further investigate the notion that the majority of the learning curve for moves to solution is attributable to a decrease in loops and backtracks over time, separate charts of the frequencies of loops, long backtracks (>6 moves) and short backtracks (≤6 moves) were constructed. These are presented in Figure 31. As can be seen, the majority of the decrease seen in moves to solution by trial is due to a reduction in the number of short backtracks made by subjects.

Figure 31 Loops, Long and Short Backtracks by Trial



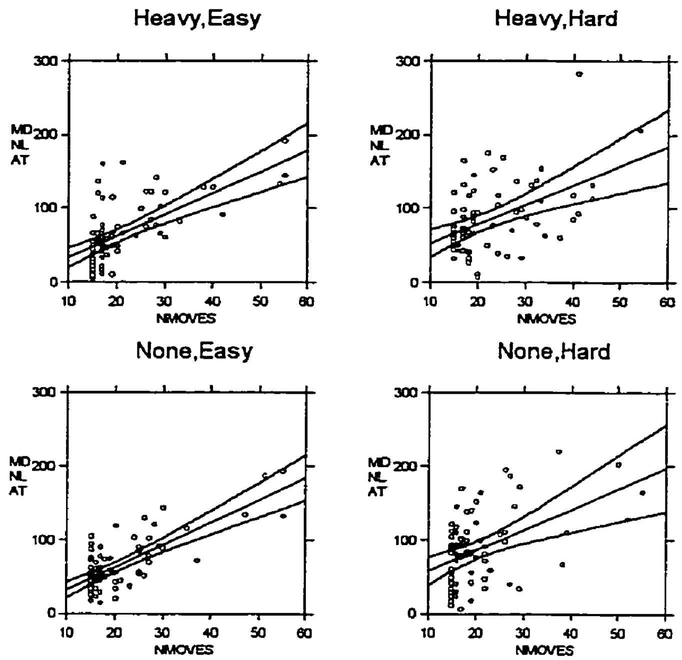
Finally, a learning curve was constructed of the mean of subjects' median move latencies across trial and presented in Figure 32. With the exception of a slight increase in median latencies on Trial 11 (the first of the transfer trials) this curve also shows a smooth decline across trials, in keeping with previous research (Groff & Saint Cyr, 1993).

Figure 32 Median Move Latencies by Trial



Plotting the relationship between moves to solution and median move latency, for each of the four experimental conditions, addressed the question of the possibility of a speed-accuracy trade-off. The results are presented in Figure 33.

Figure 33 Relationship between Speed and Accuracy



As can be seen there is a small positive relationship between move latencies and moves to solution. The 95% confidence curves on the graphs all encompass positive slopes.

The Experimental Manipulation

A split-plots factorial analysis of variance (ANOVA) was conducted with interference condition as the between-subjects effect and trial as the within-subjects effect, on the dependent variable, mean number of moves to solution. The results are summarised in Table 8 below.

Table 8 ANOVA for Mean Moves to Solution

Source	SS	df	MS	F	p	$p_{adjusted}$ Greenhouse -Geiser	$p_{adjusted}$ Huynh-Feldt
Interference	5.3	1	5.3	0.013	0.908		
Transfer	104.7	1	104.7	0.268	0.607		
Interference x Transfer	210.0	1	210.0	0.537	0.466		
Subjects(Int. x Trans.)	23452.2	60	390.9				
Trial	12625.6	14	901.8	11.154	<0.001	<0.001	<0.001
Trial x Interference	1443.2	14	103.1	1.275	0.217	0.240	0.222
Trial x Transfer	2019.7	14	144.3	1.784	0.037	0.059	0.041
Trial x Interference x Transfer	2278.1	14	162.7	2.013	0.015	0.029	0.017
Trial x Subjects (Int. x Trans.)	67916.2	840	80.9				

Greenhouse-Geisser Epsilon:	0.7291	Huynh-Feldt Epsilon:	0.9343
Effect Size r (Interference):	0.013	Counternull (Interference):	0.026
Effect Size r (Transfer):	0.065	Counternull (Transfer):	0.13
Effect Size r (I x T):	0.095	Counternull (I x T):	0.19

The only effects that were significant once adjustments were made for sphericity, and experimentwise error rate, were the typical main effect of trial, and a three-way interaction between Trial, Interference Condition and Transfer Task.

To further explore the significant three-way interaction, a separate split-plots ANOVA was conducted with interference and transfer conditions as the between-subjects effects and trial as the within-subjects effect, on the dependent variable, mean number of moves to solution, for trials 11-15. The results are summarised in Table 9 below.

Table 9 ANOVA for Mean Moves to Solution on Trials 11-15

Source	SS	df	MS	*F*	*P*	$p_{adjusted}$ Greenhouse -Geiser	$p_{adjusted}$ Huynh-Feldt
Interference	105.8	1	105.8	0.552	0.460		
Transfer	6.6	1	6.6	0.035	0.853		
Interference x Transfer	24.2	1	24.2	0.126	0.724		
Subjects(Int. x Trans.)	11493.4	60					
Trial	417.5	4	104.4	1.936	0.105	0.112	0.105
Trial x Interference	73.9	4	18.5	0.342	0.849	0.832	0.849
Trial x Transfer	201.9	4	50.5	0.936	0.444	0.438	0.444
Trial x Interference x Transfer	434.2	4	108.6	2.013	0.093	0.100	0.093
Trial x Subjects (Int. x Trans.)	12939.8	840	53.9				

Greenhouse-Geisser Epsilon: 0.9129
Huynh-Feldt Epsilon: 1.0000

As can be seen the interaction is no longer significant once one only examines TT3. As there is little point in discussing an interaction involving the level of transfer before the transfer has taken place, no further decomposition of this effect was undertaken.

It was anticipated that subjects that had spent a great deal of time searching the third corner of the state space during the ten training trials would show greater transfer to the middle peg. The relationship between percentage savings from trials 10 to 11 in moves to solution and the percentage of moves made by subjects in the third corner on trials 1-10 is plotted by experimental condition in Figure 34. Table 10 reports the associated Pearson's correlation coefficients. As can be seen there is a strong positive relationship for those in the hard transfer condition, and a strong negative relationship for those in the easy transfer condition, but only for those subjects trained under conditions of heavy interference.

Figure 34 Percentage Savings during Transfer as a Function of Interfences and Transfer Conditions and Percentage Time in Third Corner During Training

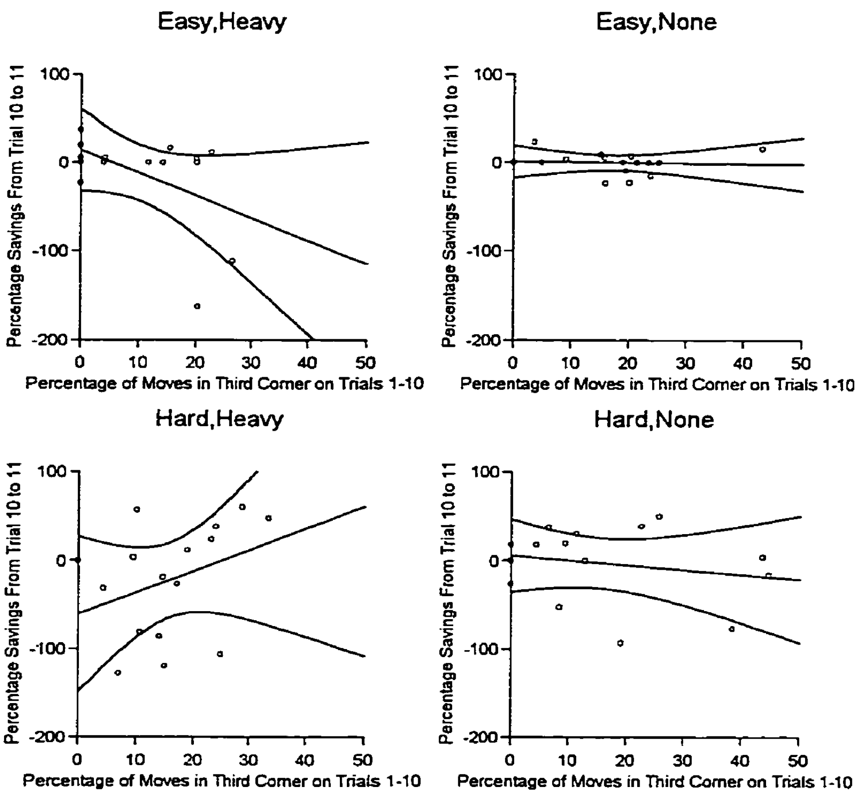


Table 10 Pearson Correlation Matrix for Percentage in Third Corner on Training Trials with Percentage Savings in Transfer Trials, by Interference and Transfer Condition

	Heavy Interference	No Interference
Easy Transfer	-0.489*	-0.058
Hard Transfer	0.347*	-0.202

A split-plots, factorial analysis of variance (ANOVA) was conducted with interference and transfer conditions as the between-subjects effects and trial as the within-subjects effect, on the dependent variable, median move latencies. The results are summarised in Table 11 below. The only significant effect is for trial.

Table 11 ANOVA for Median Move Latencies

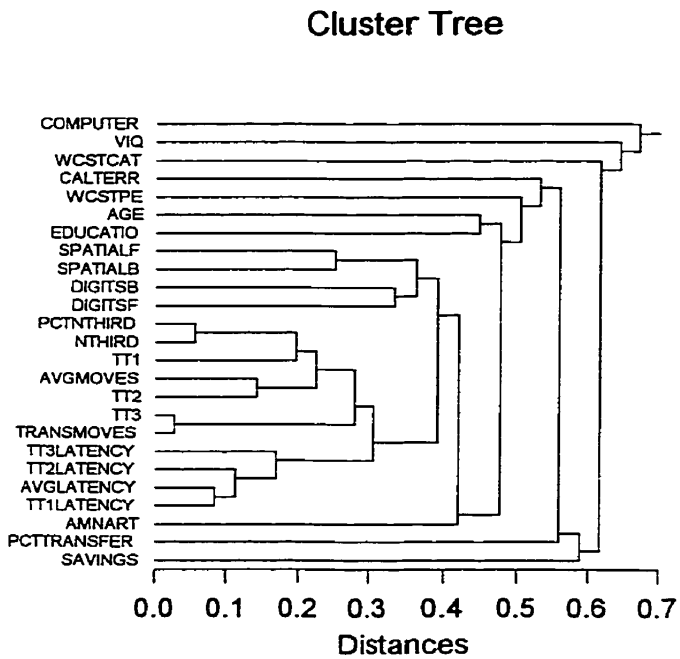
Source	SS	Df	MS	*F*	*p*	$p_{adjusted}$ Greenhouse -Geiser	$p_{adjusted}$ Huynh-Feldt
Interference	3673.8	1	3673.8	0.126	0.724		
Transfer	10867.6	1	10867.6	0.372	0.544		
Interference x Transfer	0.037	1	0.037	<0.001	0.999		
Subjects(Int. x Trans.)	17538021	60	29230.1				
Trial	2090945.5	14	149353.3	69.479	<0.001	<0.001	<0.001
Trial x Interference	28013.5	14	2001.0	0.931	0.525	0.455	0.463
Trial x Transfer	49407.4	14	3529.1	1.642	0.063	0.156	0.146
Trial x Interference x Transfer	27476.8	14	1962.6	0.913	0.544	0.466	0.475
Trial x Subjects (Int. x Trans.)	1805679.9	840	2149.6				

Greenhouse-Geisser Epsilon: 0.3227
Huynh-Feldt Epsilon: 0.3696

The Ancillary Tests

To investigate the role of individual differences in the solution of the Tower, analyses were again conducted comparing the results of the ancillary tests to measures of both moves to solution and move latency, both broken down by the segment of testing (TT1, TT2, TT3) and overall. Additional variables were entered based upon the above analyses, including measures of transfer from TT2 to TT3, and percentage time spent by subjects in the third corner of the state space on Trials 1-10. As in Experiment 1, all the variables were entered into a hierarchical cluster analysis algorithm, using a centroid linkage method and a Pearson's *r* distance metric. The results are presented graphically in the following dendrogram, Figure 35.

Figure 35 Dendrogram for Experiment 3



Again, the Tower measures, including the newly generated ones, all form a fairly homogenous and isolated cluster. In this experiment, even the AMNART is no more closely related to these measures than are the Digit and Spatial spans.

Discussion of Results

Again we have null results for the experimental manipulations, as predicted by the experimenter. Again we are faced with the dilema of the impossibility of proving null results. The solution, again, is to turn to measures of magnitude of effect, mindful of the additional corroboration of the a priori power analysis described under the first two experiments. The obtained effect size for the interference manipulation on our moves to solution variable was quite small (r= 0.013) with a small associated counternull effect size ($r_{counternull}$=0.026). Similarly, for the effect of transfer distance there was a small obtained effect size (r=0.065) and counternull statistic ($r_{counternull}$=0.13). Finally, the interaction effect (interference x transfer) was also of very small magnitude (r=0.095, $r_{counternull}$=0.19). In short, we have further confirmation of the findings of Experiments 1 and 2, that the learning on the Tower of Toronto is very robust to interference, and preserved through transfer. Thus we have further reason to conclude that the task is learned automatically and that the learning is of abstract information.

The lack of effect for the interference by trial interaction is taken as evidence for the statistical, and presumably functional, dissociability of these two issues in this context. However, one interesting finding that argues the picture might be more complex, is the presence of the linear relationships between experience of the state space during initial learning, and eventual transfer that was found to be quite strong under conditions of high interference but not otherwise. We will return to this finding in the next chapter.

Chapter 4 Conclusions and General Discussion

The Experimental Findings

The Individual Differences Variables

It is interesting to note that unlike prior research in our laboratory no clear associations could be found between any measures from the Tower and the other neuropsychological tests found in our battery. The Tower measures all clustered together and quite separate from any of the other measures for all three experimental samples. The only exception to this is the inclusion of the raw error score on the AMNART in the cluster with the latency measures on the Tower during two of the experiments. Indeed, the AMNART clustered more closely with the latency measures than did the accuracy measures in both these samples. This is interesting, in that the AMNART errors can be taken as an index of verbal IQ, albeit one that is not corrected for age or years of formal education as is the Estimated VIQ into which it is typically converted.

There is a long history of interpreting performance on problem solving tasks such as the Tower in light of theories of general intelligence. Ewert (1932) demonstrated a possible impact of general intelligence as a mediating factor in subjects' ability to use more complex instructions, and greater potential for verbalization to improve perfomance. In his study, the learning curves for errors & sidetracks (moves off of primary path) showed greatly increased efficiency with increased instructions to work verbally, but not for all subjects. Indeed the instructions seemed to increase variability, as they facilitated the performance of subjects who scored high on a concurrent test of verbal intelligence, but seemed to impede those who scored lowest. More recently, some have used variants of the disc transfer task as instruments for assessing intelligence directly (Brousek, 1971).

Generally though, studies with both normal and mentally retarded adults have tended to show only low levels of association between any Tower measure and more traditional measures of IQ (Kanevsky, 1990; Kanevsky, 1994; Spitz et al., 1985; Vernon & Strudensky, 1988). In fact, when such associations are found, they are usually only demonstrable early on in subjects' acquisition of the problem solving skill. Vernon (1988) attributed individual differences of intelligence within the framework of Sternberg's (but see also Berg & Sternberg, 1985; 1985) experiential sub-theory of intelligence, linking it to the constructs of novelty and automaticity. The theory suggests that verbal abilities give way to performance abilities, as such a task becomes increasingly automatised. Other work in developmental samples has found IQ less predictive than age of ability to solve this puzzle and indeed in some cases IQ is negatively related to performance (Kanevsky, 1994).

Nonetheless there have been those that have found correlations between individual differences in subjects' intellectual abilities and the frequency and duration of pauses on the task (Welsh, Cicerello, Cuneo, & Brennan, 1995). That alone may be sufficient to account for the relationship shown on the experiments reported here. One must take any such explanation with a grain of salt in light of the fact that the relationship disappeared in the other sample reported, and in light of the notorious problems with individual differences in performance on Tower tasks themselves (Cockburn, 1995; Groff & Saint Cyr, 1993, In Preparation; Saint Cyr et al., 1988; Saint Cyr et al., 1995).

The Learning Curves

Learning on the Tower, at least in the earliest trials, can be characterised as a gradual elimination of extraneous moves from a person's idiosyncratic solution pathway. This is consistent with much of the literature on skill acquisition which identifies error detection and correction as fundamental for the shift from early stages of skill learning to later ones (Anderson, 1988; Fitts & Posner, 1967). Learning does not seem to involve increased efficiency of strategy selection, or optimisation of solution pathway, rather it is characterised by the trimming of ornaments from a given path, presumably originally discovered by trial and error exploration of the state space. Note that this finding stands in sharp contrast to those that have suggested that sub-optimal solutions are the mark of pathology in the learning mechanism. Perretti et al administered haloperidol to YNC subjects and found that under such treatment they regularly proceduralised sub-optimal solution strategies (Peretti et al., 1997). Our findings indicate that this is perfectly normal for YNC subjects, who are quite likely to proceduralise non-optimal solution strategies.

Two previous studies had shown some evidence of loss over the 1½ hour gap between trials five and six on the task (Groff, 1992; Trepanier, 1989). In these studies there was a significant increase in moves to solution between trials five and six, and the authors concluded that subjects had lost some consciously acquired and maintained information about the task across this interval. Groff (1992) concluded that there was evidence to suggest that the curves for moves to solution and move latencies were measuring dissociable cognitive/conscious and procedural/implicit components of the task respectively. While there was no statistically significant evidence for such loss across the gap between trials five and six in the three studies here reported, it is worth noting that such an increase was at least subjectively visible in the curve obtained for experiment 2. The possible role of the interference manipulation in this experiment on this aspect of the learning curve will have to remain an open question for future investigation.

The learning curves for latency reflect the gradual elimination of backtracking events, with their attendant pauses, from a subject's chosen solution strategy. It has been demonstrated previously, that subjects pause when about to back-track a series of moves (See Chapter 3 for the most recent demonstration of this), and when confronted with a critical choice point on the Tower's State Space (Groff & Saint Cyr, In Preparation). Movements through critical choice point CCP1 (see Chapter 2 above) show the mark of being either implicitly learned move sequences, or of perceptually transparent solutions to a sub-goal once it presents itself. The pattern of move latencies at this juncture suggests a pause to either plan a sequence of moves executing the sub-goal, or at least to recognise the presence of such a sub-goal. This pause is followed by a series of rapid moves, which terminates once the sub-goal is completed, and subjects again must pause to "get their bearings" (Groff & Saint Cyr, In Preparation). These particular move sequences are presumably also perceptually transparent, once one arrives at the critical point. This does not require an elaborate interpretation such as Karat's production system (1982).

Previous studies have suggested that the learning curve for median move latencies reflects a purer measure of procedural learning on the Tower of Toronto (Groff & Saint Cyr, 1993). The current studies were not designed to specifically address this point, though at least tentative evidence is presented here in the persistence of a learning curve for latencies when only primary path moves are considered.

Careful analysis of subjects' performance while learning the task has revealed that subjects are not using anything as sophisticated as a means-end strategy, or indeed any strategy leading to optimisation of solution. Rather, individual subjects stumble upon a solution which is satisfactory, and then proceed to refine that idiosyncratic solution by the elimination of ornaments. It is likely that this is performed on-line and consciously as error detection and correction improves. This is evidenced by the gradual elimination of ornaments, but the ever present pauses at the turnaround point of backtracks.

However, in addition to this conscious elimination of ornaments from solution, the reduction in move latencies across trials when considering only primary path moves suggests the presence of an independent procedural (or implicit) learning system engaged simultaneously. The only clear evidence of conscious involvement is in the pauses (presumably for thought) at the turnaround point in a backtracking event, and at the onset and the conclusion of a learned or perceptually transparent sequence, such as CCP1. The Tower of Toronto thus seems to be more a puzzle of proceduralization than of conceptual access and this is a distinction from the Tower of Hanoi. Future research will have to examine the effect of task features on subjects learning characteristics.

The Experimental Manipulations

In the first experiment there was no significant effect of the level of transfer on either subjects' moves to solution or their median move latencies. In short, subjects were able to solve the puzzle backwards, or to the middle peg equally well, having learned to solve it on ten normal trials. A finer grained analysis on the transfer effect in the third experiment showed that the case was probably somewhat more complex (see below).

In the second experiment, there was found to be a significant effect of level of interference on subjects' median move latencies though not their moves to solution. A closer examination revealed that the nature of this effect was not one of interference from either incongruent or random associations of size and colour information in the Stroop version of the tower, but rather a facilitation of subjects' performance when the association between colour and size was congruent. Such facilitation of response time with congruent presentation is a quite common and robust finding of the general literature on the Stroop effect (MacLeod, 1991, 1992). Accordingly, it does provide evidence that the decision to use a stroop type of dual-task interference was effective, and thus lends support to the notion that subjects' immunity to negative interference on these tasks is genuine.

Finally, the third experiment addressed whether there was any possible interaction between these two factors. While a significant interaction did show up, it turned out to be a statistical artefact, as it occurred earlier than trial 11 in the data. Thus, it cannot be the result of different transfer conditions interacting with different levels of interference, as none of the subjects are transferring anything until trial 11.

We then performed a finer grained analysis on the issue of transfer. It was always open to question whether one should consider the transfer to the backward tower or the transfer to the middle peg as goal, the more difficult transfer condition. It was my hypothesis that what subjects learn during the ten trials of the tower has at least as much to do with the underlying constraints of the problem's state-space as with perceptual surface features. Accordingly I decided to test whether subjects' prior exposure to certain areas of the state space, such as exploration of the third corner on one of Trèpanier's Type IV solutions

(1989), would influence their later performance on a transfer task where that corner was now the goal. Results showed that subjects who previously made many moves in the third corner of the state space were indeed facilitated on transfer to the mid-peg solution, while those without that experience were impaired. Strangely, these findings only held for subjects whose initial experience had been under conditions of extreme interference. The conclusion then, is that there is evidence for some acquisition of familiarity with the problem's state-space and that there is some evidence for an association between this abstract learning and the degree of automaticity, but not quite as predicted in either case.

While it is, of course, impossible to find empirical evidence for the non-existence of a given effect, the results of these three experiments give fairly strong evidence that there is no impact of level of transfer or level of interference upon subjects' ability to learn the Tower of Toronto. The table below (Table 12 Counter Null Statistics (Moves to Solution)) summarizes the evidence presented in the discussion of the individual experiments. Noting again that it is impossible to conclude, from a failed null-hypothesis test, the absence of the effect tested for, one can examine the obtained effect size. To reiterate, by converting the effect sizes from the first three experiments to Pearson's r and then doubling the value one obtains what is known as the counternull statistic. This is the value of r that is equally probable as an effect size of zero, given the effect size obtained. One normally calculates this statistic to demonstrate that even though an effect didn't reach significance, a reasonably large effect size was at least as probable as an effect size of zero assumed by the null hypothesis. In the case of the three studies here reported, however, the counternull statistics are presented for a different purpose. As can be seen (Table 12 Counter Null Statistics (Moves to Solution)) the counternull statistics, and thus the effect sizes equally probable to effect sizes of zero are still quite small. This provides additional reason to be confident that our dependent measure on the Tower (in this case, moves to solution over trials) was indeed resistant to the interference effect and robust in transfer.

Table 12 Counter Null Statistics (Moves to Solution)

Experiment	Effect	*r*-counternull
1	Transfer	0.19
2	Interference	0.16
3	Interference	0.026
3	Transfer	0.13
3	Interference x Transfer	0.19

Automaticity and Abstraction

Is the Tower Learned Automatically?

As noted above James argued that habit, which enables the learning of new skills, etc. must proceed automatically (James, 1890). This sentiment has been echoed throughout the literature on skill learning (Anderson, 1983; Anderson, 1988; Fitts & Posner, 1967), reading (LaBerge & Samuels, 1974), search (Posner & Snyder, 1975), and attention (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Such theories have argued that while there may indeed be conscious, effortful processing involved in solving problems such as the tower, especially in the early stages, one becomes skilled at such a task through the operation of some automatic process. The question remains whether there is evidence for such a process at work in subjects' acquisition of problem solving skill on the Tower of Toronto.

Hasher argued that automatic processes: operate continuously; cannot be improved upon by additional practice; do not require awareness; cannot be inhibited either wilfully or by external interference; and their products are available to consciousness though their processes are not (1979). Given this list of criteria, many of which have been debated in the literature before, it was thought that the best test of the issue of automaticity could be made by forcing the cognitive resources employed in solving the tower task to compete with a source of external interference. The Stroop task has been frequently interpreted as an example of an interference effect (MacLeod, 1991, 1992; Stroop, 1935).

In both the second and third experiments reported here subjects were subjected to Stroop-type interference and did not show any effect of it, either in isolation or in interaction with their learning across time. Regardless of their Stroop condition, subjects showed the same learning curve for number of moves to solution, and with one exception, for median move latencies as well. That single exception, was the general speeding of performance in the congruent colour-size condition in experiment two. As previously noted, this sort of facilitation with congruent stimulus features is common in the literature on the Stroop effect (MacLeod, 1991, 1992). The question is whether it constitutes a vulnerability to external interference, which would argue against the notion of an automatic process in the acquisition of this skill. I would argue not. The subjects in the congruent condition displayed the same learning curve as the rest of the subjects, just generally shorter move latencies. What one must remember is that in the congruent condition on this task, subjects were essentially presented with the stimuli for a four-disk Tower of Hanoi, in addition to the Tower of Toronto. Despite the absence of instruction concerning the size of the disks, subjects could simply have solved the puzzle on that basis, rather than based on the colour rules. It is my belief that the facilitation on this condition represents the generally easier time subjects have with size coded rather than colour coded versions of tower tasks (Welsh et al., 1999).

On the basis, then of resistance to external interference there would seem to be evidence for an automatic process involved in the acquisition of skill on the Tower. It should be noted, however, that Hasher provides other criteria, which are also met by the current data. These are that automatic processes operate continuously and that their processes are not available to consciousness, though their products are. Continuous operation is visible in the smooth learning curves for moves to solution and median move latency even across intervals of up to 1 ½ hours, which were occupied with other cognitive tasks, presumably occupying working memory capacity and thus preventing any form of directed rehearsal. The criterion of cognitive impenetrability is more difficult to establish, but it should be noted that no debriefing questions administered to subjects, either here, or in prior studies (Groff, 1992; Saint Cyr & Taylor, 1992; Trepanier, 1989) has ever demonstrated subjects' awareness of how they learned to solve the puzzle, or confidence that they could teach their method to others.

Is the Learning, That of Abstract Information?

Mindful of Shanks and Saint-John's (1994) exhortation to not conflate the issues of automaticity and abstraction, we must address separately the issue of whether the learning on the Tower is of abstract information. It was the initial intention of the first experiment to contrast the transfer to solving the problem backwards, with that of solving to the middle peg. While solving the problem to the middle peg seems perceptually to involve many of the same sorts of movements as solving to the third peg, it involves navigating through an entirely different corner of the state-space. In contrast, solving the problem backwards seems perceptually completely dissimilar to solving it forwards, but actually involves navigation along precisely the same pathways through the state-space. In any event, however, subjects' performance on both transfer tasks was indistinguishable. Traditionally, from Reber (1976) on, the mere presence of transfer has been taken as evidence of learning of abstract concepts rather than incidents (Adams, 1987; Dominey, Ventre Dominey, Broussolle, & Jeannerod, 1997; Gomez, 1997; Willingham et al., 1989). And thus, the fact that subjects' performed as well on the more distal transfer conditions as on solving an additional five trials of the same task would count as evidence of such abstract learning. There are those, however, who argue that learning of quite simple associations or covariances in stimuli would be sufficient to account for most instances of transfer in the literature (Perruchet & Pacteau, 1990; Perruchet et al., 1997). It was largely to answer these critiques that both a solving the task backwards, and a solving the task to the middle peg conditions were employed in the first experiment. In the former case, the only similarity between the transfer condition and the original ten trials is that the solution moves through the same parts of the state space, the perceptual and motor sequences would be entirely different. The fact that there is no difference in subjects' ability to transfer to that condition and any of the other conditions, suggests that what is being learned has more to do with the deep structure of the task than with surface features, simple covariances of which might be learned.

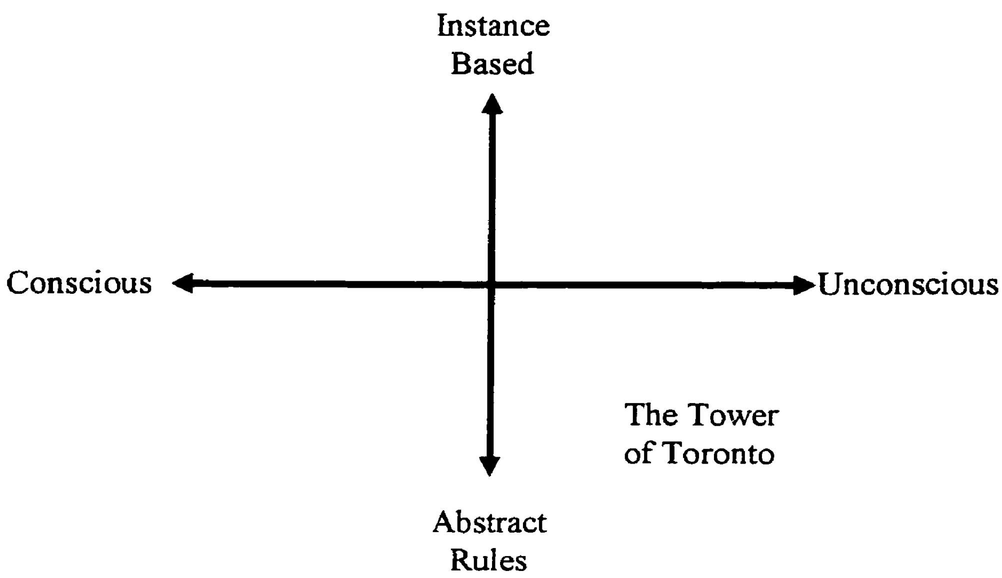
A further test of subjects' learning of the state-space was made in experiment three. Here it was found that subjects who had extensive prior experience in the third corner of the state-space during their learning trials, by making many type four solutions, for example, showed facilitated transfer to solving the puzzle on the middle peg. The relationship also held for subjects lacking this prior experience, in other words who made most Type 1 and 2 solutions, and then transferred to solving the puzzle identically. What was most striking about these findings, however, as noted above, is that these associations were only present for those subjects who's initial practice trials had been made under conditions of maximal interference. It must await future investigation to answer why this should be so, though perhaps some speculation is possible. Under the heavy interference conditions, with working memory being taxed by distracting, irrelevant stimuli, it is perhaps understandable that facilitation of an effect taken to be emblematic of non-conscious, procedural learning should be augmented.

General Concluding Remarks

Knowing How and Knowing That, But Knowing What?

It would seem then, that there is sufficient evidence to tentatively conclude that there are implicit processes at work in acquiring the cognitive skill to solve the Tower of Toronto puzzle. The primary focus of this paper has been to address the weakness noted by Shanks and St. John (1994; 1996) that claims for implicit processes often confound the issues of automaticity of the learning with the abstract nature of the learning. Accordingly two tests, transfer for abstraction and interference for automaticity, were made in an effort to examine these issues separately. All the evidence from the current studies implies that at least part of the process of learning this task proceeds automatically, and that at least some of what is learned is abstract in nature. Returning to our initial model then, we would locate the Tower of Toronto task in the lower right quadrant of our Cartesian space. It must be noted, of course that these axes are relative, only the levels of interference and the distance of transfer actually employed in this study. The revised model is present in Figure 36.

Figure 36 The Location of the Tower of Toronto on our model



Possible Next Steps...

As is often the case with any piece of research, as many questions are raised as seem to be addressed. Among those issues raised by these studies that would seem to warrant further work are:

1. Exactly how automatic and abstract is the learning? Addressing this issue will require replication and extension of the direct findings of these studies using even more extreme forms of interference and even more distal transfer conditions. For just one possibility, there has been some evidence that cross modal interference can

impair procedural learning, as a secondary tone-counting task has been found to show some, though not complete, interference in learning on Nissen's SRT task (Frensch, Lin, & Buchner, 1998).

2. Can explanations such as Perruchet and Pacteau's (1994; 1990; 1997) appeal to covariation learning be completely eliminated? It should be noted that even the best evidence for transfer of abstract knowledge here presented, might be susceptible to charges that learning of simple associations could as easily account for the results as appeals to abstract notions such as state-space. The issue of how generalisable learning must be, before one calls the object of that learning abstract is a thorny one, unlikely to succumb to simple experimental investigation. Further conceptual work on this issue is clearly warranted, indeed needed.

3. Why did the pattern of results for transfer and prior state-space experience occur only in the presence of Stroop interference? Is the issue one of diminished cognitive resources, presumed to correspond to higher levels of interference, breeding a more process pure implicit learning situation or is there a more complex explanation needed? Prior research in other cognitive domains, such as reading, has occasionally shown this peculiar pattern of facilitation under conditions of cognitive load (Paap & Noel, 1991), but those counter-intuitive findings have certainly been hotly contested.

4. Given the evidence presented that this task taps cognitive processes of procedural learning, what can be said of the neural substrate of learning to solve a problem. The vast majority of the neuroimaging studies reviewed in Chapter 2, have focused on regions of cortical activation, ranging from dosolateral to mesial frontal, the insula,

and only occasionally the subcortical regions of the striatum and cerebellum. It must be remembered that essentially all of these imaging studies have been conducted with the Tower of London, a task which we have already demonstrated is quite different from the Towers of Hanoi and Toronto, both in terms of cognitive processes involved, and in terms of sensitivity to neurological impairment. Accordingly, it would be interesting to conduct a series of imaging studies using the Tower of Toronto, which seems to be less a task of planning than the Tower of London, and to see whether there is more evidence of sub-cortical, and in particular striatal involvement in its acquisition.

All of the above issues, and doubtless more that the astute reader will have gleaned for him or herself will have to be the subject of extensive future work. For the present, we are left with the conclusion that there is reason to believe that implicit processes, involving the automatic learning of abstract knowledge are involved in learning to solve the Tower of Toronto.

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