DISSERTATION

EXAMINING COMPONENT PROCESSES OF PERFORMANCE ON THE TOWER OF LONDON

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY NANCY A. ZOOK ENTITLED EXAMINING COMPONENT PROCESSES OF PERFORMANCE ON THE TOWER OF LONDON BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

EXAMINING COMPONENT PROCESSES OF PERFORMANCE ON THE TOWER OF LONDON

Three experiments examined the component processes underlying performance on a widely used executive function task, the Tower of London (TOL). All of the experiments examined the relationship of TOL performance to measures of working memory and inhibition. Experiment 1 examined the contributions of working memory, inhibition, and fluid intelligence to performance on the TOL. It was found that although working memory and inhibition did not significantly contribute to TOL performance, fluid intelligence did account for a significant amount of variance. In contrast, Experiment 2 found that, overall, the working memory and inhibition variables accounted for 34% of the variance in TOL performance. Experiment 2 also showed that the underlying problem structure affected accuracy on the task, but the hypothesis that there would be a stronger relationship between external measures of inhibition and problems with conflict moves and suboptimal solution paths was not supported. Experiment 3 found that as the secondary task became more difficult, performance was less accurate and slower in both tasks. These results support a working memory maintenance component to Tower of London performance. There was not an interaction between move number and the number of letters in Tower of London accuracy indicating that complexity and working memory maintenance may not have a strong relationship.

Based on these findings, it is concluded that the commonly held view that executive function as measured by the Tower of London can be conceptualized in terms of working memory and inhibition needs to be reexamined. The finding that problem structure affects complexity in the Tower of London problems is important both in theoretical and practical terms.

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INTRODUCTION

Examining the Construct of Executive Function

The term executive function (EF) has been widely used by psychologists in recent years to describe a complex cognitive domain. However, controversy has arisen over an exact definition of executive function and the component cognitive processes it entails (Denckla, 1996; Stuss & Benson, 1987; Welsh & Pennington, 1988). As the number of studies on executive function has increased, it seems as though more questions than answers have emerged (Welsh, Friedman & Spieker, in press).

Historical Relation to the Prefrontal Cortex

Executive function has its roots in neuropsychological evaluations of frontal lobe function. Early research done by Feuchtwanger (1923, as cited in Benton, 1991) and Bianchi (1920, 1922, as cited in Benton, 1991) indicated that damage to the prefrontal cortex had implications for global personality function, as well as difficulties monitoring impulsive behavior, poor serial and parallel processing, attentional deficits, and problems integrating behavior. Goldstein (1936, 1944, as cited in Benton, 1991) added to these studies, suggesting that the following cognitive functions are mediated by the prefrontal cortex: initiating action, anticipation and planning, resistance to suggestion, flexibility, self-monitoring and analytical problem solving. Later, Luria's theory of the brain's functional systems was developed after examining patients with frontal lobe damage and observing the resultant impaired behavior (Luria, 1966, 1973). Luria postulated that there are three basic brain-based units used in information processing: the arousal unit, the sensory input unit, and the output/planning unit. These units develop, beginning around age six, from basic planning, monitoring and control behavior to the more abstract, complex problem solving seen in puberty and early adulthood. The sensory input unit and the output/planning unit can be further divided into primary, secondary, and tertiary areas, with each level indicating increasing complexity. In this model the tertiary area (located in the prefrontal cortex) would be responsible for planning and executing complex and abstract problems (Luria, 1973). Luria noted that patients with frontal damage seemed to exhibit specific deficits related to planning, or future-oriented, goal-directed behavior, despite normal performance on intelligence tests. More recently, in a review of EF, Welsh et al. (in press) pointed out that historically patients with frontal damage performed normally on tests examining attention, memory, language and general intelligence, yet were unable to plan ahead or did not exhibit goal-directed behavior.

The complexities of the frontal lobes, anatomically as well as functionally, make them a challenging part of the brain to study. Given the history of EF and its relation to damage to the frontal areas, it is not surprising that EF and the frontal lobes, more specifically the prefrontal cortex, are difficult to separate in the literature. In much of the literature, it is assumed that EF reflects frontal lobe processing, and specifically activity in the prefrontal cortex (PFC). However, Stuss and Alexander (2000) warn that this relationship has not yet been established. Indeed, Owen, Schneider and Duncan (2000) assert that although it is likely that the frontal cortex has areas with specific specialization, these may or may not map onto current cognitive models of EF. They note that neuropsychological and neuroanatomical studies on the link between PFC and EF have been inconsistent. Hobson and Leeds (2001) point out that if it were possible to map

EF directly onto specific brain areas than we would not still be debating a definition of EF, how to test EF, and its usefulness in a clinical sense. They also caution that neuroimaging studies may be overinterpreted within existing cognitive models of EF. Researchers are working from poorly defined theoretical models, as well as tasks that lack specificity, and therefore may draw conclusions that fit nicely with their model while another researcher may interpret the results to favor their own model.

Historical research on frontal lobe damage also leaves us with several gaps in our understanding of EF (Welsh et al., in press). First of all, there are problems inherent in taking observations of behavior in an individual with brain damage and making assumptions of underlying functioning or processing in an intact brain. Second, neuropsychologists developed assessment tools that were based on their sensitivity in terms of detecting frontal lobe damage, not based on the underlying cognitive processes thought to be affected. In order to further our understanding of executive function, it is useful to merge research from neuropsychology and cognitive psychology.

How Can Executive Function Be Conceptualized?

Articles from the behavioral domain use different definitions of EF, and an agreed upon operational definition of EF has not yet emerged. However there are some commonly held ideas about the skills that underlie EF, Welsh (2002) suggests that these are: “planning, inhibition, monitoring, and flexibility to recruit a range of basic cognitive processes such as attention, perception, language and memory”(p.143). These skills are common to some of the most popular theories of EF, as outlined below.

Norman and Shallice's (1986) Supervisory Attentional System

One influential information-processing conceptualization of executive function was proposed by Norman and Shallice (1986). Norman and Shallice begin their discussion of a "theory of action" by discussing the difference between controlled and automatic processes and the role of attention. Any theory must recognize that automatic responses should at times be overridden so that an individual can control the behavior in order to meet the goal. Executive behavior can be seen as necessitating active monitoring and a mechanism that allows shifting between a continuum of automatic and controlled processes when necessary to maximize performance. The role of perceptual experiences as well as learning is incorporated into this model. Two processes are proposed to work together to select and control action sequences. The first process, a lower level contention scheduling system, comes into play when an action sequence is undemanding or routine. The second process, the supervisory attentional system (SAS), is used for novel situations that require strategic planning. These situations require the activation and inhibition of schemas. Performance is driven by selecting the appropriate schema and thus avoiding what Norman and Shallice term as "conflicts in performance" (p.3).

From these basic ideas Norman and Shallice (1986) propose that the activation of schemas can be represented using a processing structure that they call a horizontal thread. The important point of this depiction of processing is that it can have underlying principles or components that can be specified and tested. In situations in which multiple schemas are activated, the mind must have some way of selecting a response, whether it is appropriate or not in the midst of all of this conflict. Schemas are activated once a sufficient value is reached via attentional resource allocation. A schema will then be used until such time that it is consciously rejected, until the goal is reached, or until adequate cognitive resources to maintain the activation are no longer available. Deliberate attention does not consciously determine which schemas to activate or inhibit, rather it sways the activation values of the horizontal threads, thus indirectly influencing which schemas are verified and selected. Norman and Shallice propose that the SAS is particularly important in situations that are novel or complex. The SAS directs the contention scheduling system and provides a means to exert influence or control over attention by influencing the output levels and in turn the selection of schemas. Baddeley (1986) sees the SAS as equivalent to the central executive of his working memory model.

Norman and Shallice's (1986) SAS has commonalities with other working definitions of EF. Goal directed performance in novel, complex situations requires planning, inhibition, monitoring of behavior, and cognitive flexibility. The model also includes the often-neglected influence of motivation.

Neuropsychological findings support the SAS model. There is evidence that the anterior cingulate could be the location of the SAS (Gazzaniga, Ivry and Mangun, 1998). Although compelling, it should be noted that there are fundamental weaknesses with the SAS. Wood and Grafman (2003) suggest that there are specific criteria that theories should meet in order to provide a useful model of function. These criteria include specifying the type of model (representational vs. processing), identifying whether it is supported by biology, whether it is testable, whether it is supported by data, and whether it is feasible in evolutionary terms. Norman and Shallice's (1986) SAS model falls short in several of these areas, especially in terms of being testable.

Executive Function, Working Memory, and Inhibition

Another debate in cognitive psychology is whether EF can be accounted for by working memory and/or inhibitory processes. One or both of these processes are often included in neuropsychological and cognitive models of EF. Pennington (1994) defines working memory as an "arena" where information is held, manipulated and updated throughout the problem-solving process. Similary, Salthouse (2000) defines working memory as "the ability to maintain information about the task requirements, such as goals, assignments of decisions to responses, etc., while also performing the relevant operations without time-consuming pauses to re-orient oneself and reinstate the task goal or the appropriate response assignment rule" (p. 39).

The neural basis of working memory is not entirely known, but neural networks in the striatum and prefrontal cortex have been implicated (Moscovitch, 1994). Some of the first evidence that the prefrontal cortex is involved in memory was seen in Jacobsen's (1936) work with primates. He found that monkeys with lesions to the prefrontal cortex were adversely affected on delayed response and alternation tasks. These tasks contained a delay condition that challenged the animals' ability to recall a specific event. Current research also shows that patients with damage to this area have specific memory impairments. A prefrontal patient may have difficulties organizing information and retrieving less remarkable or less available information, whereas they are able to easily access salient experiences (McDonald, Ergis, & Winocour, 1999).

Memory abilities appear to contribute to other cognitive deficits typically found in patients with prefrontal insult, such as planning, interference, and shifting sets. The shared component underlying these cognitive deficits appears to be the ability to consciously use strategic processes that necessitate the use of stored information. Wincour and Mosocovitch (1990) compared the problem-solving deficits of rats with damage to the prefrontal cortex to rats with hippocampal damage. The rats were first trained and tested on a Hebb-Williams maze and then tested 30-days later on the same maze, as well as a new maze. Both groups showed deficits on initial learning. The hippocampal group transferred the learned skills to both mazes, but did not have an additional advantage when retested in the original maze. However, the prefrontal group could recall specific information about the original maze and thus were able to use this prior knowledge to their advantage when retested in the maze, but lacked the ability to manipulate the newly learned skill so that it could be applied to a new situation. This implies that damage to the prefrontal cortex results in a deficit specific to working memory, memory that is responsible for holding information for a brief period to support ongoing activities (Baddeley, 1986).

In Baddeley's (1991) working memory model, working memory consists of a limited capacity "central executive" and two "slave systems". The central executive directs information into one of the slave systems, the phonological loop (which processes verbal information) or a visuo-spatial sketchpad (which processes nonverbal material). Information is stored passively in these slave systems until it is needed. When the information is needed, the central executive must use its relatively limited capacity to retrieve and manipulate information as required by the task. The central executive also integrates information and determines what is or is not relevant for storage and manipulation. Experiments using neuroimaging, for example, positron emission topography (PET), support the view that the frontal lobes are important for working memory. D'Esposito et al. (1995) found prefrontal cortex activation during dual tasks but not single tasks. There are presumably higher working memory demands in the dual task because of the need to obtain and manipulate information and shift attention between two tasks.

Another cognitive construct that is widely thought to be central to executive function is inhibition (Welsh & Pennington, 1988; Luria, 1973). Inhibition can be defined as the suppression of irrelevant information, responses, or strategies. Inhibition has also been described as the ability to inhibit the selection of incorrect alternatives while engaged in a cognitive task (Ridderinkhof & van der Molen, 1997). Radvansky, Zacks and Hasher (1996) state that inhibition suppresses "…the activation of goal-irrelevant information so that such information is less likely to have access to working memory and so that irrelevant information that does not enter working memory, as well as previously relevant information that is no longer useful is quickly removed" (p.143). Knight et al. (1999) collected evidence from behavioral, electrophysiological and blood flow techniques indicating that the prefrontal cortex can "sculpt behavior through parallel inhibitory and excitatory regulation of neural activity in distributed neural networks" (p. 159). In support of the role of the frontal lobes in inhibition, other researchers have also found a lack of cognitive inhibition in patients with frontal lobe damage (Damasio & Anderson, 1993; Fuster, 1997; Grafman et al., 1993; Stuss & Benson, 1984).

Pennington, Benneto, McAleer, and Roberts (1996) propose that EF can be defined by the combination or interaction of working memory and inhibition. This view is based on the seminal work of Hasher and Zacks (1988) and others. Hasher and Zacks state that the efficient operation of working memory requires inhibitory mechanisms that limit what information is allowed into working memory for completion of a goal. In a normally functioning system, information that is off-the-goal path is discarded, or if it is allowed into working memory, it will be dampened. By contrast, inefficient inhibition allows off-the-goal information to enter working memory and be maintained rather than dampened.

Conway and Engle (1994) suggest that individuals have a limited amount of attentional resources to execute both working memory and inhibition processes. They found that when placed in a nonconflict situation, subjects were more likely to be able to execute working memory operations than when placed in conflict situations. They explained that only those individuals with the resources available for both inhibition and working memory were successful. The conflict situation requires more operating space for inhibition; this leaves less space available for storage and working memory.

Recent connectionist models have found evidence that supports the idea that working memory and inhibition interact in goal-directed behavior. The more inhibition is needed to suppress an incorrect response, the more strain is placed on working memory (Cohen & Servan-Schreiber, 1992; Dehaene & Changeux, 1991; Kimberg & Farah, 1993; Levine & Prueitt, 1989). The theoretical link between inhibition and working memory is also supported by neuroimaging studies suggesting that both types of processes are mediated by the prefrontal cortex (Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999; Goldman-Rakic, 1987; Hasher & Zacks, 1988; Prabhakaran, Narayanan, Zhao & Gabrieli, 2000; Ranganath, Johnson, & D'Esposito, 2003). However some research has found that working memory and inhibition are only moderately correlated and that much of the variance in EF performance accounted for by these processes is unshared (e.g., see

Welsh et al., 1999). A recent structural equation model of executive function (Welsh et al., 2001) examined the latent structure of EF in a large sample of neurologically normal, young adults using a battery of ten tests. They proposed that the correlated constructs of working memory and inhibition would predict variance in "higher order" constructs such as planning, flexibility, and rule indication. The results suggested that working memory and inhibition are moderately correlated. Working memory was found to explain more of the variance in planning and rule induction than inhibition, and both working memory and inhibition explained approximately the same amount of variance in the flexibility factor.

Given the inconsistencies in the literature, both theoretically and empirically, a valid question is whether the construct of executive function, as it is currently conceptualized, is still useful and relevant in cognitive psychology. One way to address this question is to further investigate the cognitive processes that are theoretically associated with EF. It is also necessary to investigate exemplar tasks in order to assess the degree of association they have with the frontal lobes and the component aspects of cognition that are thought to underlie EF.

Measurement of Executive Function

Without a clear conceptualization of EF, it is difficult to develop tests that are thought to reflect EF. This is not a new problem in cognitive psychology. Constructs such as attention and memory remain loosely defined. However, there are some rather significant problems that are specific to EF research. Rabbitt (1997) notes that without a concise definition of EF or a clear understanding of the core processes, it is not possible to establish a hierarchy of function that is testable. Bryan and Lucszc (2000) note the circular reasoning used in the development of many EF tasks stating that tests are used to assess EF because frontal lobe patients are show a decrement in performance on them and tests are deemed to be sensitive and valid because they are sensitive to frontal lobe impairments. Tasks are used based on their ability to differentiate frontal and non-frontal populations rather than being developed in order to test the theoretical processes behind EF. In neuropsychology, a battery of tests is required to show executive dysfunction because there is not an accepted prototypical EF task.

Another problem is that tasks are said to reflect EF because they include planning, monitoring, inhibition, working memory, etc. However, tasks like the Towers of London and Hanoi that logically should have these components show weak and inconsistent relationships with working memory and inhibition (Welsh, Satterlee-Cartmell, & Stine, 1999). Burgess (1997) observes that even subtle, seemingly minor changes to EF tasks can result in changes in behavior most likely due to the peripheral systems involved in the task. In other words, because EF is a higher-order cognitive processing skill, tasks cannot *just* measure the higher components because basic skills are also inherent in the task. The complex, multifactoral nature of EF tests make it virtually impossible to develop a test that is sensitive and specific. Combined, these factors make it difficult to define EF in terms of task performance.

The Tower of London as a Measure of EF

Although the difficulties of defining and developing executive function tasks need to be acknowledged, there are several tasks that are believed to tap into the processes associated with EF. One of these, the Tower of London, was originally designed by Shallice (1982) to measure frontal lobe function and the executive processes presumed to be mediated by this brain system (Stuss & Benson, 1984; Welsh & Pennington, 1988). The Tower of London is considered by some to be an exemplar measure of executive function, the set of skills that subserve goal-directed, future-oriented behavior (Goel & Grafman, 1995; Lezak, 1995; Krikorian, Bartok, & Gay, 1994; Welsh, Satterlee-Cartmell, & Stine, 1999). The task requires the person to generate the shortest sequence of moves to transform a start position of three balls arranged on pegs into a predetermined goal state configuration. Cohen (1996) suggested that working memory is needed for formulating, maintaining and applying and revising plans. Presumably, the individual generates a move plan in working memory, where it also is executed, monitored, and revised prior to action. Many of the problems present a situation in which a direct move to the goal must be inhibited for successful solution.

Originally the Tower of London consisted of 12 problems ranging from 2-5 moves (Shallice, 1982). The Tower of London recently was revised in order to increase its reliability (Schnirman, Welsh, & Retzlaff, 1998). The resulting task, the Tower of London-R (see Figure 1.1), has an internal consistency reliability (Cronbach alpha) of .794. The test-retest reliability of the Tower of London-R was found to be r = .70 (Schnirman et al., 1998). The revised task consists of 30 problems ranging from 4 to 6 moves and is thought to be suitable for further experimental and clinical use (Schnirman et al., 1998).

Neuroimaging research suggests that the Tower of London is sensitive to frontal cortical function. Positron Emission Tomography (PET) studies indicate that working on the Tower of London task activates the frontal association cortex (Owen, Doyon, Petrides, & Evans, 1996). Dagher, Owen, Boecker, and Brooks (1999) found that regional cerebral blood flow (rCBF) levels in the dorsolateral prefrontal cortex and lateral premotor cortex correlated with the complexity of the Tower of London problems attempted by the adult participants. Using functional Magnetic Resonance Imaging, Lazeron et al. (2000) found that in the active, planning condition of the Tower of London, there was activation of the dorsolateral prefrontal cortex. Not surprisingly, it has been found that the performance of patients with frontal lobe lesions is impaired on a computerized version of the Tower of London (Owen, Downes, Sahakian, Polkey, & Robbins, 1990). Clinical groups with structural or neurochemical anomalies involving the frontal lobe, such as schizophrenia, obsessive-compulsive disorder, and Parkinson's disease exhibit deficits on Tower of London tasks as well (Andreasen et al., 1992; Dagher et al., 1999; Veale, Sahakian, Owen, & Marks, 1996).

Carder, Handley, and Perfect (2004) note that although the Tower of London is frequently used as an EF task, the question of what cognitive processes underlie performance on the task remains unanswered. Welsh et al. (1999) also note that researchers often claim that tower tasks such as the Tower of London are sensitive to frontal lobe damage because they tap into working memory and inhibition (Goldman-Rakic, 1987; Goel & Grafman, 1995) or both cognitive processes (Roberts & Pennington, 1996). However, there is inconsistency in the literature as to the role of working memory and inhibition in the Tower of London. A recent study utilizing correlational and multiple regression techniques found that working memory and inhibition variables explained over one-half of the variance in TOL-R (a revised version of the Tower of London) performance (Welsh et al., 1999). However, in a study examining the relationship between the TOL-R and other executive function tasks as well as intelligence, it was found that the TOL-R loaded with intelligence subtests instead of executive function tasks of inhibition (Stroop Interference) and working memory (Spatial Span on WAIS-III) (McGarraugh, 2000).

Additional research is therefore needed on the underlying cognitive processes that are involved in the performance of the Tower of London. One particularly important avenue for future research is to examine the structural properties of the Tower of London task and the corresponding performance. Although much attention has focused on the different versions of the Tower of London (i.e. 3-peg versus 5-peg), it may also be important to question the current scoring methods and manner of assessment used with this task. For example, scores are currently based on global performance on the task. However, recent studies (e.g. Kaller, Unterrainer, Rahm & Halsband, 2004) seem to indicate that the underlying cognitive processes used to solve problems may vary as a function of the structural task properties at the level of the individual problem. If this is the case, it could mean that complexity may be related to not only additional moves needed to solve problems, but also the underlying structure of the problem.

Overview of the Current Study

To address the issues and inconsistencies discussed above, the present study further examines the component processes involved in performance on the Tower of London, focusing on the contributions of working memory and inhibition. The amount of variance in Tower of London performance that is explained by working memory and inhibition measures will be examined using traditional regression analysis. In addition, the study will examine how the type, or structure of a problem, affects performance. If there is a difference in performance based on the type of problem, analyses will be conducted in order to identify whether specific problems seem to recruit more inhibitory or working memory resources than others. Due to inconsistencies as to the role of working memory in Tower of London performance, a new paradigm utilizing dual task methodology will also be employed. This new methodology will allow for incremental variations in working memory load so that the impact on Tower of London performance can be assessed. This type of methodology is particularly useful since the results can be analyzed without relying on correlational or regression analyses. The use of different methodologies and statistical analyses will potentially address the inconsistencies currently found in the literature. The theoretical as well as practical implications of the results will be considered, both in terms of Tower of London performance and current conceptualizations of executive function.

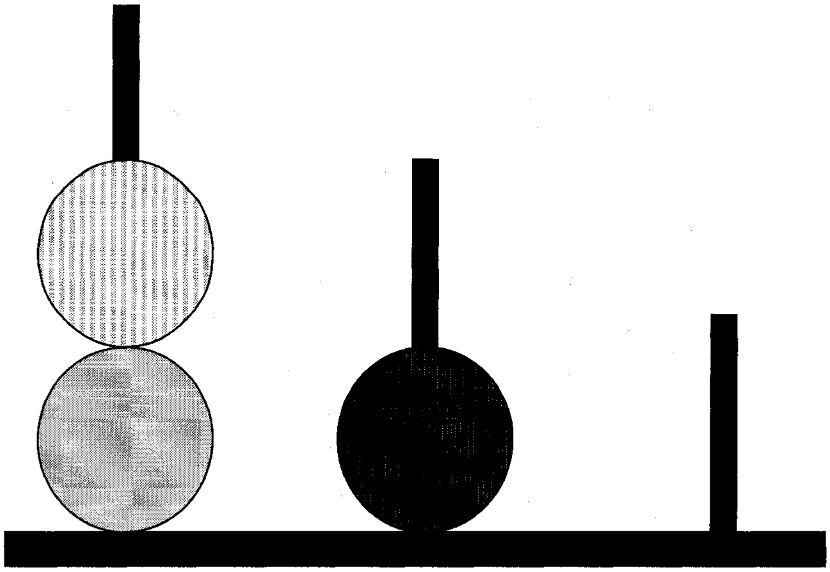

Figure 1.1. The Tower of London-Revised apparatus.

CHAPTER II

OUTLINE OF EXPERIMENTS

This chapter outlines three experiments that attempt to understand the cognitive processes that underlie Tower of London performance, specifically the contributions of working memory and inhibition. To the extent that the Tower of London measures the construct of EF, the results also have potential implications for the current conceptualizations of EF.

Experiment 1

The first experiment examined the relations between working memory, inhibition, and the Tower of London and Tower of Hanoi, using two working memory measures and two inhibition measures. Past research has been very inconsistent, at times showing a strong relationship between working memory and inhibition and at other times showing only a weak relationship (e.g., Welsh et al., 1999; Miyake et al., 2000). This study also investigated the role of fluid intelligence in the Tower tasks in order to identify the overlap between the constructs of EF and fluid intelligence.

Experiment 2

The aim of the second experiment was to further examine the influence of inhibition within the Tower of London task. Inhibition was examined using conflict moves (moves that require the individual to move initially move away from the endgoal or final solution in order to solve the problem correctly) and suboptimal alternatives (moves which allow the problem to be solved using one or two suboptimal solutions). This design allows for the direct examination of the relationship between an internal measure of inhibition and external measures of working memory and inhibition. This experiment also examined how performance changed as the number of moves needed to solve the problems increased and if there was a difference between performance on conflict, suboptimal, and nonconflict moves as a function of number of moves.

Experiment 3

The third experiment examines performance on the Tower of London under dual-task conditions. If performance with two tasks results in a decrement in performance on one task, then it can be concluded that the tasks use the same or similar overlapping resources. By systematically varying the working memory load using a modified version of the Sternberg Item Recognition Task (Sternberg, 1966), the role of working memory maintenance in solving the Tower of London was addressed.

CHAPTER III

EXPERIMENT 1

The purpose of Experiment 1 was to examine the relationship between working memory, inhibition, and two tower tasks, using two working memory measures (Visual Span and Memory Cards) and two inhibition measures (Stroop interference and Colorado Card Sort perseverative errors). Past research by Welsh, Satterlee-Cartmell, and Stine (1999) investigated the contribution of working memory and inhibition to performance on the Tower of London and Tower of Hanoi tasks, and results showed that several working memory and inhibition measures were related to Tower of London performance, but only one inhibition measure was related to Tower of Hanoi performance.

A secondary purpose of Experiment 1 was to examine the contribution of fluid intelligence to performance on the Tower of Hanoi and Tower of London tasks using Matrix Reasoning as the measure of fluid intelligence. Duncan, Burgess, and Emslie (1995) argued that the construct of executive function maps closely onto fluid intelligence. Consistent with this view, Rabbitt and Lowe (2000) recently showed that spatial working memory and visual memory tasks no longer accounted for significant variance in performance on executive function tasks from the Cambridge Automated Neuropsychological Test Battery (CANTAB) after fluid intelligence was taken into account. In the present study, a fluid intelligence measure was included to determine whether or not working memory and inhibition predicted performance on the Tower of Hanoi and Tower of London tasks beyond that explained by fluid intelligence.

Method

Participants

Eighty-five college students (32 males and 53 females) participated in partial fulfillment of the requirements for an introductory psychology course. The mean age of participants was 19 years (*SD* = 1). Participants were first asked to fill out a consent form and a demographic questionnaire that included age, date of birth, educational history, and medical history in order to screen for serious head injuries that may interfere with performance. With the exception of Matrix Reasoning, all tasks were administered on computers. The Tower of Hanoi and Tower of London tasks were given first, with the order of these two tasks counterbalanced, followed by the Colorado Card Sort Test, Memory Cards, Matrix Reasoning, Visual Span Task, and Stroop Task.

Tasks

Tower of Hanoi. The computerized five-ring Tower of Hanoi task from the Colorado Assessment Tests (CATs) was administered following the protocol outlined in Davis and Keller (1998). Participants were instructed to move disks across three vertical pegs from a start position to a goal configuration in the fewest number of moves, with a minimum of 31 moves required. Four trials were given, each requiring that all of the disks be moved from the left peg to the right peg, with the constraints that a larger disk could not be placed on top of a smaller disk and only one disk could be moved at a time. A trial was terminated upon successful completion of the problem or 100 moves. The dependent measure of interest was the average number of excess moves (beyond the minimum of 31) across the four trials.

Tower of London (TOL). The computerized CATs version of the TOL was used, consisting of three 2-move items and six 3-move, 4-move and 5-move items for a total of 21 problems (see Davis & Keller, 1998). The number of pegs varied from 3 to 5 with 7 trials given for each type of puzzle. The TOL requires participants to maneuver balls from a start position to a goal position in as few moves as possible with the following constraints: (1) only one ball may be moved off of a peg at a time, (2) the balls must always be positioned on one of the pegs, and (3) the number of balls that can be placed on a peg varies from 1 to 4. Performance was measured by calculating the average number of excess moves (moves needed over minimum solution) across the 21 problems.

Colorado Card Sort. The Colorado Card Sort task was also administered. The Colorado Card Sort is a computer-based variation of the Wisconsin Card Sorting Test (cf. Heaton, Chelune, Talley, Kay, & Curtiss, 1993) and was programmed using the CATs software package (Davis & Keller, 1998). Participants were required to match a card in the center of the screen with one of four cards located at the top of the screen that served as references. The cards were sorted based on a rule that used color of the card background, color of the word, or the name of the word. Once ten consecutive sorts were achieved, the rule was changed without warning and the process repeated until six sets were completed or 128 cards were sorted. For the purposes of this study, the dependent variable of interest was the number of perseverative errors, the number of times a participant repeated an incorrect response after corrective feedback. A computational model by Amos (2000) suggests that frontal lobe dysfunction results in an increase in perseverative responses that is indicative of an inability to inhibit prepotent responses. Others have also suggested that the perseverative errors index may be used as a measure of inhibitory dysfunction (e.g., Everett, Lavoie, Gagnon, & Gosselin, 2001).

Memory Cards. The computer-based CATs Memory Card task was used as a measure of nonverbal working memory (Davis & Keller, 1998). Twenty-four cards were presented on the screen, each with an abstract shape on the non-visible side of the card. The 24 cards consisted of 12 matching pairs. Participants selected two cards at a time in an attempt to find a matching pair. Upon selection, the shapes on the cards were shown for several seconds, and then the process was repeated. If a matching pair was found, that pair of cards was removed from the set. The participants were instructed to match pairs of cards as quickly and accurately as possible in order to obtain all 12 matching pairs. The number of moves required to match all cards on the first trial of the task was used as a measure of working memory.

Matrix Reasoning. Matrix Reasoning, a task from the Wechsler Abbreviated Scale of Intelligence, was also administered (Wechsler, 1999). Matrix Reasoning has been found to be a reliable and valid measure of fluid intelligence, correlating .81 with another common measure of fluid intelligence, Standard Progressive Matrices (Wechsler, 1997). The task consists of four types of problems: pattern completion, classification, analogy, and series completion. Participants were presented 35 test items in a booklet. For each item, they were instructed to look at the presented matrix, and from the five options given, choose the one that best completed the problem. Two sample items were given at the beginning of the task to familiarize participants with these types of problems. The maximum score on the Matrix Reasoning Test was 35, with each item worth one point.

Visual Span. The computer-based CATs Visual Span task was used as an additional measure of nonverbal working memory and is similar to the visual span task in the Wechsler Memory Scale-Revised (Wechsler, 1987), with both a forward and reverse span test included (Davis & Keller, 1998). Eight boxes were displayed on the screen and these boxes were illuminated in a specific sequence that participants were to try to duplicate. The task began with a sequence of two and this sequence length was maintained until the participant missed two trials (at which time the task was terminated) or correctly duplicated eight sequences (at which time the sequence length was increased by one). The maximum sequence length achieved was used as the dependent variable.

Stroop Task. A computer-based Stroop Task was created to measure susceptibility to interference and lack of inhibitory control (Stroop, 1935). Participants were given lists of color names (red, blue, and green) printed in color ink. Two types of trials were given: congruent trials in which the color name and ink color were the same and incongruent trials in which the color name and ink color were different. For each trial, participants were to press a color coded key on the keyboard that corresponded to the color of the ink and do so as quickly as possible. Response inhibition was measured by subtracting the average response time for the congruent condition from average response time for the incongruent condition.

Results

The means, standard deviations, and ranges for each of the measures are shown in Table 3.1[1]. The alpha level for all statistical analyses was set at .05. Pearson product moment correlations were computed between the two Tower tasks and between each

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[1] Tables 3.1 – 3.4 have been reprinted from Zook, N.A., Davalos, D.B., DeLosh, E.L., & Davis, H.P. (2004). Working memory, inhibition, and fluid intelligence as predictors of performance on Tower of Hanoi and London tasks. *Brain and Cognition, 56,* 286-292 with permission from Elsevier.

Tower task and the other dependent measures (for a full correlation matrix, see Appendix I). The correlation between Tower of Hanoi performance (excess moves) and Tower of London performance (excess moves) was significant, $r(85) = .27$, $p < .05$. Note, however, that the unshared variance between the two tasks was 93%. As shown in Table 3.2, performance on the Tower of Hanoi was significantly correlated with Visual Span, Memory Cards, CCS perseverative errors, and Matrix Reasoning. There was also a moderate but non-significant correlation between Tower of Hanoi performance and Stroop interference. In contrast, performance on the Tower of London was significantly correlated with just two of these variables, Stroop interference and Matrix Reasoning.

Table 3.1

Mean and Standard Deviation for Each Variable.

Variable	*M*	*SD*	*Min*	*Max*
Tower of London (Excess Moves)	9.26	7.79	0	30
Tower of Hanoi (Excess Moves)	133.27	59.68	10	274
CCS Perseverative Errors	10.40	8.69	1	46
Stroop Interference	209.19	136.24	-60	534
Visual Span	18.16	3.68	4	26
Memory Cards	27.52	4.91	19	44
Matrix Reasoning	30.24	2.61	22	34

Note: CCS = Colorado Card Sort.

Table 3.2

Correlations between Performance on the Tower Tasks and Each of the Working Memory and Inhibition Measures

Measures	Tower of Hanoi	Tower of London
Visual Span	-.41**	-.02
Memory Cards	.22*	.00
Stroop Interference	.18	.22*
CCS Perseverative Errors	.28*	.04
Matrix Reasoning	-.39**	-.40**

Note: CCS = Colorado Card Sort. *$p < .05$, **$p < .01$.

Reliability Analysis

A Cronbach's alpha internal consistency reliability analysis was conducted. The reliability analysis revealed a low Cronbach alpha, Alpha = .22, See Appendix II for inter-item correlation coefficients.

Regression Analyses

Following the method used by Rabbitt and Lowe (2000), linear regression analyses were then conducted for each of the predictor variables as they related to performance on the Tower of Hanoi and Tower of London. The results of these analyses are shown in Table 3.3. Both the composite working memory measure and composite inhibition measure significantly predicted performance on the Tower of Hanoi, but neither significantly predicted performance on the Tower of London. Among the individual working memory and inhibition measures, CCS perseverative errors, Visual Span, and Memory Cards accounted for a significant amount of variance on the Tower of Hanoi task, but only Stroop interference accounted for a significant amount of variance on the Tower of London. All inhibition and working memory measures were then entered into a linear regression model to assess the variance accounted for by all working memory and inhibition measures. This composite measure accounted for 25% of the variance on the Tower of Hanoi but only 5% of the variance on the Tower of London. Matrix Reasoning accounted for 15% and 16% of the variance on the Tower of Hanoi and Tower of London, respectively.

A forced-entry hierarchical regression analyses with Matrix Reasoning performance as the first predictor in the regression and the working memory and inhibition composite measures as second predictors was conducted (see Table 3.4). These analyses allowed us to determine whether or not the working memory and inhibition measures accounted for variance on the Tower of Hanoi and Tower of London tasks beyond that accounted for by Matrix Reasoning. The working memory measure, inhibition measure, and a working memory/inhibition composite significantly predicted Tower of Hanoi performance after Matrix Reasoning was accounted for. None of these measures significantly predicted Tower of London performance after Matrix Reasoning was accounted for. To address the reverse question of whether or not Matrix Reasoning accounted for variance beyond that of the other measures, additional hierarchical regression analyses were conducted with the working memory and inhibition measures as the first predictors in the regression and Matrix Reasoning as the second predictor (see Table 3.4). These analyses showed that Matrix Reasoning significantly predicted Tower of Hanoi and Tower of London performance after controlling for the working memory, inhibition, and composite working memory/inhibition measures.

A regression analysis was also conducted to determine whether or not the variance on the Tower of Hanoi and Tower of London tasks that is predicted by Matrix Reasoning is shared variance. With Matrix Reasoning performance as the dependent variable, a forced-entry hierarchical regression analysis was conducted with Tower of Hanoi performance as the first predictor and Tower of London as the second predictor. Tower of Hanoi performance accounted for 15% of the variance on Matrix Reasoning and Tower of London performance accounted for an additional 10% of the variance, indicating that the Tower of Hanoi and Tower of London capture different variance in Matrix Reasoning.

Table 3.3

Results of Linear Regression Analyses with Tower of Hanoi and Tower of London Excessive Moves as Dependent Variables and Working Memory Measures, Inhibition Measures, and Matrix Reasoning Scores as Predictor Variables

	Tower of Hanoi		Tower of London	
Predictor Variables	*F*	R^2	*F*	R^2
Working Memory Composite	9.10**	.18	0.02	.00
Visual Span	17.55**	.17	0.02	.00
Memory Cards	4.41*	.05	0.00	.00
Inhibition Composite	5.22*	.11	2.17	.05
Stroop Interference	2.81	.03	4.20*	.05
CCS Perseverative Errors	6.65*	.07	0.08	.00
Working memory/Inh	6.76**	.25	1.06	.05
Matrix Reasoning	15.14**	.15	16.41**	.16

Note: CCS = Colorado Card Sort, Inh = inhibition., $*p < .05$, $**p < .01$.

Table 3.4

Results of Forced-Entry Hierarchical Regression Analyses Showing the Additional Variance Accounted for by the Second Predictor After Controlling for the First Predictor.

	Tower of Hanoi		Tower of London	
Regression Equation	*Incr.* R^2	*Total* R^2	*Incr.* R^2	*Total* R^2
Matrix Reasoning + Working Memory	.13*	.28*	.01	.17*
Matrix Reasoning + Inhibition	.08*	.23*	.03	.19*
Matrix Reasoning + Working Memory/Inh	.18*	.33*	.04	.20*
Working Memory + Matrix Reasoning	.10*	.28*	.17*	.17*
Inhibition + Matrix Reasoning	.12*	.23*	.14*	.19*
Working memory/Inh + Matrix Reasoning	.08*	.33*	.15*	.20*

Note: Inh=inhibition. *$p < .01$

Discussion

The present study examined the contributions of working memory, inhibition, and fluid intelligence to performance on the Tower of Hanoi and Tower of London tasks. Results revealed that working memory and inhibition composite measures accounted for a significant amount of variance on the Tower of Hanoi, but neither accounted for a significant amount of variance on the Tower of London. The results were consistent across individual measures (Visual Span and Memory Cards) in showing that working memory significantly contributed to Tower of Hanoi performance but not Tower of London performance. The results were less conclusive in the case of inhibitory processes, given that one inhibition measure (CCS perseverative errors) significantly contributed to Tower of Hanoi but not Tower of London performance, but a second inhibition measure

(Stroop interference) significantly contributed to Tower of London but not Tower of Hanoi performance.

Conclusions regarding the contributions of working memory and inhibition to the tower tasks should be considered with caution, however. When attempting to parcel out the component processes involved in complex cognitive tasks such as the Tower of Hanoi or Tower of London, one approach is to analyze a global measure of task performance in terms of the variance accounted for by performance on other tasks that are thought to be relatively pure measures of component processes. There are at least three problems with this approach. First, the role of a single component process may be underestimated when examining a global measure of performance, especially if that component process only comes into play on a subset of moves or problems. Second, component cognitive processes may interact, have opposing effects on overall performance, or compete with one another for limited cognitive resources. This would limit the ability to estimate the contribution of any one cognitive process to overall task performance. Third, measures of component processes are rarely, if ever, pure measures. A common assumption, for example, is that performance on the Stroop task primarily reflects the operation of inhibitory processes. Yet there is accumulating evidence that Stroop interference reflects multiple cognitive processes and that the relative contributions of these processes vary according to task conditions (e.g., see Lindsay & Jacoby, 1994).

These issues may explain why there are often inconsistencies across studies that attempt to isolate the component cognitive processes that underlie performance on neuropsychological tests and executive function tasks. The present study, when compared to a similar study by Welsh et al. (1999), exemplifies this point. Welsh et al. used different versions of the Tower of Hanoi and Tower of London, as well as different measures of working memory and inhibition, than those used here. Although Welsh and colleagues also observed a dissociation between Tower of Hanoi and Tower of London performance, the pattern of results was only partially consistent with that reported here, such that inhibition measures significantly correlated with Tower of Hanoi performance, but both working memory and inhibition measures correlated with Tower of London performance.

Turning to the contribution of fluid intelligence to Tower of Hanoi and Tower of London performance, Matrix Reasoning scores accounted for a significant amount of variance on both tower tasks, even after controlling for the variance explained by working memory and inhibition performance. The hypothesis tested in the current study was whether contributions of working memory and inhibition to Tower of Hanoi and Tower of London performance would be substantially reduced or eliminated once fluid intelligence was taken into account, following the pattern of results obtained by Rabbitt and Lowe (2000) using the CANTAB. Regression analyses showed that neither inhibition nor working memory measures significantly predicted variance on the Tower of London after accounting for Matrix Reasoning, whereas both working memory and inhibition continued to be significant predictors of Tower of Hanoi performance. It appears, then, that general fluid intelligence may be a better predictor of Tower of London performance than the working memory and inhibition measures, but all three constructs may be important to Tower of Hanoi performance.

An additional finding of interest pertains to the differences observed for Tower of Hanoi and Tower of London tasks, two tasks that are often assumed to be highly similar and elicit similar cognitive processes. Tower of Hanoi and Tower of London performance was only moderately correlated, such that 93% of the variance across the two tasks was unshared, comparable to the 84% unshared variance reported by Welsh et al. (1999). The Tower of Hanoi and Tower of London tasks also captured different variance on Matrix Reasoning. In addition, different measures predicted performance on the Tower of Hanoi versus the Tower of London (see Tables 3 and 4). Whereas fluid intelligence was the primary predictor of Tower of London performance (with no other measures accounting for variance beyond that of Matrix Reasoning), fluid intelligence, working memory, and inhibition measures were all significant predictors of performance on the Tower of Hanoi. This may be because the Tower of London was comprised of novel problems on each trial, whereas the Tower of Hanoi involved repeated presentation of the same problem, such that success on the Tower of Hanoi was more strongly dependent on observers' ability to learn which maneuvers produce excess moves and should therefore be inhibited. Thus, although the two tasks are thought to measure executive function, these results suggest that they tap into different cognitive resources.

The key finding of the present study is the suggestion that different task structures may elicit different types of executive processes. Whereas fluid intelligence was the primary predictor of performance on the Tower of London, fluid intelligence, working memory, and inhibition were all significant predictors of performance on the Tower of Hanoi. These results must be considered preliminary, however, given that global measures of tower performance were used and given concerns about the process-pure assumptions of the component measures.

CHAPTER IV

EXPERIMENT 2

Given the commonly held belief that working memory and inhibition are important to performance on tower tasks, the findings of Experiment 1 were quite surprising in showing that working memory and inhibition did not significantly contribute to performance on the Tower of London. As discussed in the previous chapter, part of the reason for this unexpected finding may be that a global measure of TOL performance was used, underestimating the role of working memory and inhibitory processes that are recruited for some specific moves and some specific problems. Experiment 2 examines the role of inhibition in the Tower of London task by examining the relationship between an *internal measure* of inhibition and external measures of working memory and inhibition.

Many researchers have suggested that performance on the Tower of London partially reflects the ability to inhibit inappropriate moves (e.g. Welsh et al., 1999, Bagley, 2001). The inhibition of inappropriate responses may be especially important on so-called conflict moves, those moves in which there is "an apparent mismatch between the end goal of the problem and a current subgoal" (Carder et al., p.1460). Thus, as a way of addressing the possibility that global performance measures underestimate the role of inhibition in Tower of London performance, the present study examines performance on conflict versus nonconflict problems. The study adopts the general approach used in

Experiment 1, but examines the relationship between conflict-move performance and external measures of working memory and inhibition.

In addition, this study will also examine the Tower of London in terms of the number of suboptimal solutions. Kaller et al. (2004) define suboptimal solutions as moves "which allow one to solve the problem within one to two additional moves" (p. 464). Their analysis of preplanning time found that problems having suboptimal solutions had increased planning time compared to problems without suboptimal alternatives. Suboptimal solutions presumably compete with the optimal solution and must be inhibited in order to obtain the correct solution. Kaller et al. therefore conclude that specific problem structure, such as problems with a higher number of suboptimal alternatives, may show impairments above and beyond that seen in other types of problems.

It is hypothesized that there will be significant relationship between problems with conflict-moves, as well as problems with suboptimal solution paths, and external measures of inhibition. This relationship is expected to be stronger than what is observed when comparing global TOL performance measures and the external measures. Based on work by Pennington (1994, 1998, Pennington et al., 1996), there is also reason to expect that as more moves are needed to solve the problem there will be a decrement in performance on the conflict and suboptimal moves but not the nonconflict problems. This is based on Pennington's view that working memory and inhibition directly compete for limited cognitive resources. As such, when more inhibitory processes are recruited (in problems with a conflict move), additional demands are placed on working memory, causing a decline in performance.

Method

Participants and procedure

Fifty-one college students (27 females, 24 males; mean age = 19.47, *SD* = 1.57) participated in this study in partial fulfillment of the requirements for an introductory psychology course. Participants were asked to fill out a consent form and a demographic questionnaire that included age, date of birth, educational history, and medical history in order to screen for serious head injuries or illness that may interfere with performance. Participants were tested on personal computers. The Tower of London was administered followed by the other four tasks in random order and total testing time took approximately one hour. After completing the tasks, the participants were asked if they had seen any of the tasks presented.

Tasks

Tower of London-Revised. A computerized version of the Tower of London was administered, using problems from the Tower of London-revised (Schnirman et al., 1998) and several new problems[2]. The objective of the Tower of London-R task is for the participant to reconfigure three different-colored balls on three pegs of different heights. This constrains the number of balls that may be placed on each peg (i.e., the smallest peg can fit only one ball, the middle peg can hold up to two balls, and the tallest peg can hold all three balls). In addition, only one ball may be moved at a time and the balls must always be held on one of the three pegs during the move sequence. Participants are told that they must transform the start configuration into the goal state in a predetermined number of moves while adhering to these rules.

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[2] Due to the use of conflict moves and suboptimal goal paths (taken from Unterrainer et al., 2004) as an experimental manipulation, it was necessary to use 5-and 6-move problems not found in the Tower of London-Revised.

Participants were presented with twenty-four problems, half needing five moves to solve the problem, half needing six moves. For the twelve problems of each type, four had a conflict move as the first move; four had more than two suboptimal solution paths; and four did not have a conflict move and had one or fewer suboptimal moves. Within each move level, the 3 types of problems were given in random order. Participants were told the number of moves required for solution of each problem. The primary measure was accuracy on the problem. In addition, the number of excess moves, or moves over the minimum number needed, was recorded as well as the average planning time for each trial.

Colorado Card Sort (CCS). The Colorado Card Sort task was also administered. The CCS is a computer-based variation of the Wisconsin Card Sorting Test (cf. Heaton, Chelune, Talley, Kay, & Curtiss, 1993) and was programmed using the CATs software package (Davis & Keller, 1998). Participants were required to match a card in the center of the screen with one of four cards located at the top of the screen that served as references. The cards are sorted based on a rule using color of the card background, color of the word, or the name of the word. Once ten consecutive sorts are achieved, the rule was changed without warning and the process repeated until six sets were completed or 128 cards were sorted. For the purposes of this study, the dependent variable of interest was the number of perseverative errors, or the number of times a participant repeated an incorrect response after corrective feedback. A computational model by Amos (2000) suggests that frontal lobe dysfunction results in an increase in perseverative responses that is indicative of an inability to inhibit prepotent responses. Others have also suggested that perseverative errors may be used as a measure of inhibitory dysfunction (e.g., Everett, Lavoie, Gagnon, & Gosselin, 2001).

Stroop Task. A computer-based Stroop Task (Stroop, 1935) was used to measure susceptibility to interference and lack of inhibitory control. Participants were given lists of color names (red, blue, and green) printed in color ink. Two types of trials were given: trials in which the ink color was black and participants were required to press the color-coded key on the keyboard corresponding to the name of the color and incongruent trials in which the color name and ink color are different. For each trial, participants pressed a color-coded key on the keyboard that corresponds to the color of the ink and do so as quickly as possible. Response inhibition was measured by subtracting the average response time for the black ink condition from average response time for the incongruent condition.

Visual Span. The computer-based CATs Visual Span task was used as an additional measure of nonverbal working memory and is similar to the visual span task in the Wechsler Memory Scale-Revised (Wechsler, 1987), with both a forward and reverse span test included (Davis & Keller, 1998). Eight boxes were displayed on the screen and these boxes were illuminated in a specific sequence that participants were to try to duplicate. The task began with a sequence of two and this sequence length was maintained until the participant missed two trials (at which time the task was terminated) or correctly duplicated eight sequences (at which time the sequence length was increased by one). The maximum sequence length for both forward and backward span achieved was used as the dependent variable.

Self-Ordered Pointing Test. The computer-based CATs Self Ordered Pointing Test (SOPT) was used to assess working and strategic memory (Spreen & Strauss, 1998). The test consists of a series of twelve trials in which a set of stimulus items (abstract images) are arranged in a grid on a display. The arrangement of stimulus items was varied from trial to trial. On each trial the participant was asked to point to an item that they have not pointed to on a previous trial. Errors (pointing to an item that was previously pointed to) and response latencies were recorded. Petrides and Milner (1982) found subjects with frontal lobe lesions to be significantly impaired on this task when compared with normal controls and those with temporal lobe lesions.

Results

Descriptive Statistics

Means and standard deviations for each of the tasks are listed in Table 4.1. Means and standard deviations of TOL performance as a function of the number of moves needed to solve the problem and move type are listed in Table 4.2.

Table 4.1.

Variable	*M*	*SD*	*Min*	*Max*
Tower of London (Total Correct)	11.51	4.61	3	23
Tower of London (Excess Moves)	60.55	33.98	1	154
CCS Perseverative Errors	10.18	7.84	1	37
CCS Total Errors	31.71	21.9	3	79
Stroop Interference	186.17	119.85	14.08	617.83
Visual Span, Forward	10.20	2.38	1	14
Visual Span, Backward	8.96	2.04	0	13
Visual Span, Total	19.16	3.32	10	26
SOPT, Error	1.47	1.10	0	5
SOPT, Time out	.59	.64	0	2
SOPT, Percentage Correct	82.82	10.40	58.33	100
SOPT, Rule Break	.63	.78	0	3

Table 4-2.

Variable	*M*	*SD*	*Min*	*Max*
5-Move Nonconflict	2.04	1.04	0	4
5-Move Conflict	2.39	1.11	0	4
5-Move Suboptimal	2.08	1.31	0	4
6-Move Nonconflict	2.10	1.17	0	4
6-Move Conflict	1.65	1.09	0	4
6-Move Suboptimal	1.25	1.11	0	4
Total Nonconflict	4.14	1.82	1	8
Total Conflict	4.04	1.67	1	8
Total Suboptimal	3.33	2.08	0	8

Reliability Analysis

A Cronbach's alpha internal consistency reliability analysis was conducted for the TOL task. The reliability analysis revealed a high Cronbach alpha, Alpha = .79. See Appendix IV for inter-item correlation coefficients.

TOL Performance

A 2 (number of moves) x 3 (problem type) repeated measures ANOVA was conducted in order to see if there were differences in performance based on number of moves and problem type. A significant difference was found for number of moves [$F(1, 50) = 30.16$, $p < 05$, $MSE = .642$, partial $\eta^2 = .38$; see Figure 4.1] with 5-move problems ($M = 6.5$) solved more often than 6-move problems ($M = 5$) and the type of problem [$F(1, 50) = 5.92$, $p < 05$, $MSE = .829$, partial $\eta^2 = .11$]. Contrasts revealed a significant difference between nonconflict ($M = 4.14$) and suboptimal problems ($M = 3.33$) [$F(1, 50) = 8.79$, $p < 05$, $MSE =$, partial $\eta^2 =$] as well as conflict ($M = 4.04$) and suboptimal moves [$F(2, 100) = 8.79$, $p < 05$, $MSE = 2.89$, partial $\eta^2 = .15$] but not between conflict moves and nonconflict problems. An interaction between the number of moves needed to solve the problem and the type of problem was also found, $F(2, 100) = 6.22$, $p < 05$, $MSE = .978$, partial $\eta^2 = .11$].

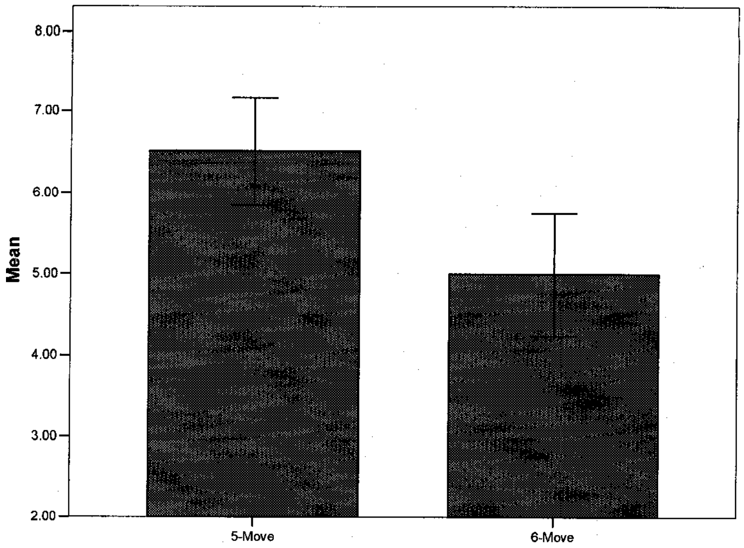

Figure 4.1. Mean TOL accuracy (out of 12) for 5- and 6-move problems; error bars represent 95% confidence intervals.

Within the 5-move problem set, a repeated measures ANOVA was conducted and found no significant difference between the different problem types . An analysis of the 6-move problems found a significant difference [$F(2, 100) = 13.12, p < .05, MSE = .692$, partial $\eta^2 = .21$] between the types of problems (See Figure 4.2). Contrasts showed that the nonconflict problems were solved significantly more often than the conflict and suboptimal problems [$F(2, 100) = 6.43, p < .05, MSE = 1.61$, partial $\eta^2 = .11$] and [$F(2, 100) = 24.92, p < .05, MSE = 1.45$, partial $\eta^2 = .33$] and conflict problems were solved more often than suboptimal problems [$F(1, 50) = 7.24, p < .05, MSE = 1.08$, partial $\eta^2 = .13$].

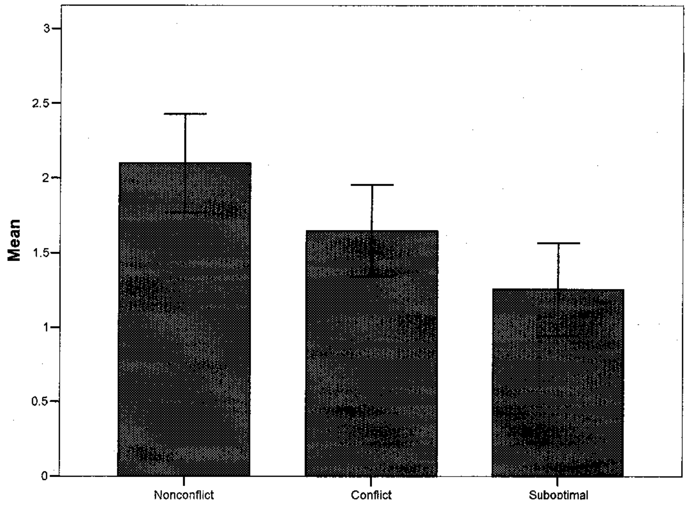

Figure 4.2. Mean TOL accuracy (out of 4) by problem structure for 6-move problems; error bars represent 95% confidence intervals.

Contributions of Working Memory and Inhibition

As in study one, hierarchical linear regression analyses were conducted in order to examine the contribution of the external measures to performance. A regression analysis examining overall performance on the Tower of London found that the working memory and inhibition variables together accounted for 34% of the variance. When examining the amount of variance according to type of trial, it was found that working memory and inhibition accounted for 42% of the variance in the nonconflict problems, 17% of the variance in the conflict trials and 27% of the variance in the suboptimal trials. A separate regression analysis showed that the working memory composite was not a significant predictor of total performance on the TOL or performance on specific types of trials. The inhibition composite was, however, a significant predictor in overall performance (27%), performance on nonconflict trials (35%), and performance on suboptimal trials (15%). The results of these analyses are shown in Table 4.3.

Table 4.3

	Tower of London							
	Overall Performance		6-Move Nonconflict Trials		6-Move Conflict Trials		6-Move Suboptimal Trials	
Predictor Variables	*F*	R^2	*F*	R^2	*F*	R^2	*F*	R^2
WM Composite	1.76	.17	2.26	.17	1.62	.12	2.25	.17
Visual Span	1.36	.05	2.21	.08	.47	.02	2.74	.10
SOPT	3.9*	.15	3.18*	.12	2.71	.10	2.13	.09
Inhibition Composite	5.63**	.27	8.18**	.35	1.95	.11	2.74*	.15
Stroop	.10	.00	.03	.00	.46	.01	.76	.02
CCS	9.13**	.28	10.32**	.30	2.49	.09	4.75*	.17
Working memory/Inh Composite	2.58*	.34	4.21**	.42	1.22	.17	2.19	.27

Note: CCS = Colorado Card Sort, Inh = inhibition., *$p < .05$, ** $p < .01$.

Preplanning Time

The average pick up time, or the time the participant examines the starting state of the problem before their first move, was analyzed as a measure of preplanning time (for means and standard deviations, see Table 4.4). A within-subjects 2 (number of moves) x 3 (type of problem) repeated measures ANOVA was conducted in order to identify whether there were significant differences in planning time as the number of moves increased and the type of problem changed. There was not a significant main effect for number of moves (5-Move $M = 2.59$; 6-Move $M = 2.39$). There was a significant main effect for the type of problem [$F(2, 100) = 19.14, p < .05, MSE = .440$, partial $\eta^2 = .28$], however, and the interaction between number of moves and type of problem was also significant [$F(2, 100) = 4.53, p < .05, MSE = .586$, partial $\eta^2 = .08$]. For 5-move problems, there was an effect of type of problem [$F(2, 100) = 15.83, p < .05, MSE = .582$, partial $\eta^2 = .24$; See Figure 4.3]. Contrasts indicated significant differences between nonconflict and conflict problems with nonconflict problems requiring more planning time [$F(1, 50) = 14.39, p < .05, MSE = 1.13$, partial $\eta^2 = .22$], and between conflict and suboptimal problems [$F(1, 50) = 36.12, p < .05, MSE = .979$, partial $\eta^2 = .42$] with suboptimal problems taking longer. There was no difference in planning time between the suboptimal and nonconflict problems. For 6-move problems, an effect of type of problem was also found [$F(2, 100) = 4.23, p < .05, MSE = .445$, partial $\eta^2 = .08$; see Figure 4.4]. Contrasts found no significant difference between conflict and nonconflict problems. However, a significant difference was found between suboptimal and nonconflict problems [$F(1, 50) = 6.18, p < .05$; $MSE = .995$, partial $\eta^2 = .11$] and between suboptimal and conflict moves [$F(1, 50) = 5.05, p < .05, MSE = 1.012$, partial $\eta^2 = .09$], with suboptimal problems taking longer in both cases.

Table 4.4

Variable	*M*	*SD*	*Min*	*Max*
5-Move Nonconflict	2.69	1.48	.88	10.02
5-Move Conflict	2.12	.83	.88	4.88
5-Move Suboptimal	2.96	1.50	1.07	8.88
6-Move Nonconflict	2.27	1.27	.72	6.98
6-Move Conflict	2.30	1.54	.67	6.63
6-Move Suboptimal	2.61	1.67	.73	8.24
Total 5-Move	2.59	1.15	1.16	7.07
Total 6-Move	2.39	1.40	.71	6.64

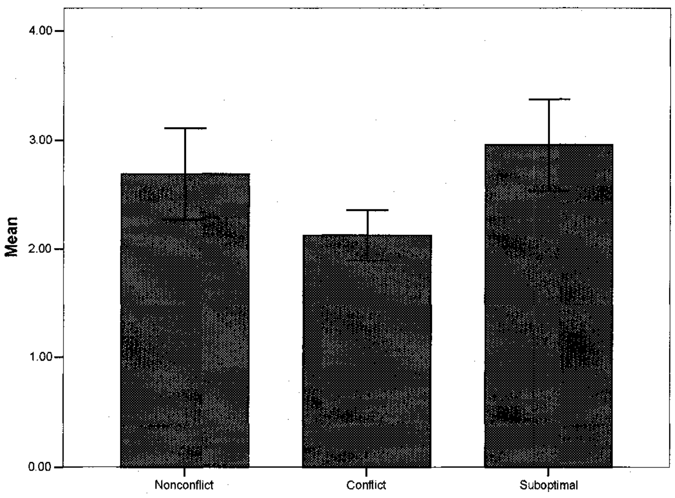

Figure 4.3. Mean preplanning time by problem structure for 5-move problems; error bars represent 95% confidence intervals.

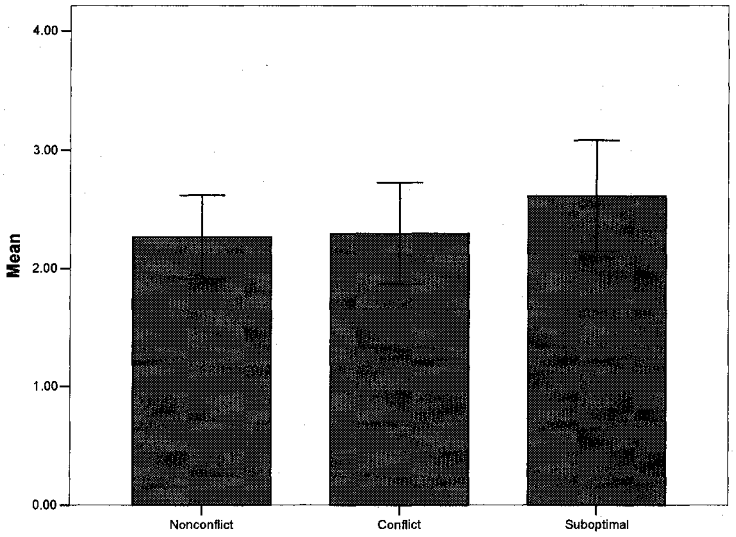

Figure 4.4. Mean preplanning time by problem structure for 6-move problems; error bars represent 95% confidence intervals.

Further regression analyses were conducted that included preplanning time. Preplanning time explained 45% of the variance in overall Tower performance [$R^2 = .45$, $F(1, 50) = 40.71, p < .05$]. Within the 6-move problems, nonconflict preplanning time explained 27% of the nonconflict problem variance [$R^2 = .27$, $F(1, 50) = 18.062, p < .05$.], conflict preplanning time explained 9% of the variance [$R^2 = .09$, $F(1, 50) = 4.793$, $p < .05$.] and suboptimal preplanning time explained 32% of the variance [$R^2 = .32$, $F(1, 50) = 22.868, p < .05$.].

Discussion

Overall, the working memory and inhibition variables accounted for 34% of the variance in TOL performance. This finding is somewhat consistent with Welsh et al.'s (1999) study which found that working memory and inhibition variables accounted for 55% of Tower of London performance, but inconsistent with Experiment 1 which found that working memory and inhibition variables accounted for only 5% of the variance. Like Experiment 1, the working memory measures did not account for a significant amount of variance in global TOL performance. The inhibition composite measure did account for a significant amount of variance in global TOL performance, unlike Experiment 1. It should be noted that the Tower of London versions used in this study and in the Welsh et al. study were similar 3-peg versions of the task, whereas the version used in Experiment 1 used 3 to 5 pegs, potentially explaining these overall differences across experiments.

The key hypothesis of Experiment 2 was that that there would be a stronger relationship between external measures of inhibition and problems with conflict moves and suboptimal solution paths than between external measures of inhibition and global TOL performance. The results did not support this hypothesis. Although problems with conflict moves and suboptimal solutions paths were more difficult, the inhibition composite measure and combined working memory/inhibition composite actually explained more variance in overall Tower of London and nonconflict move performance than suboptimal and conflict problem performance.

Carder et al. (2004) state that conflict moves require more inhibitory processes when there is “a mismatch between the end goal of the problem and a current subgoal” which necessitates moving the ball away from the goal position when it could be placed in the goal position. Goel and Grafman (1995) also contend that difficulty with conflict moves is a failure of inhibition, not planning. Similarly, when looking at suboptimal alternatives, Kaller et al. (2004) suggest that these problems have alternatives that “compete with the optimal solution…and require one to inhibit its realization and to proceed in the search for an optimal solution” (p. 464). Therefore, the smaller relationship between conflict/suboptimal moves and inhibitory measures than between nonconflict moves and inhibitory measures is surprising.

It was also hypothesized that as more moves were needed to solve a problem, the decrement in performance on the conflict and suboptimal problems would be more pronounced. This hypothesis was supported by the data. Although there was no difference in performance between the different types of problems in the 5-move condition, in the 6-move condition, there was a significant difference between types of problems. Nonconflict problems were solved at a higher rate than conflict and suboptimal problems. However, the regression results do not support the contention that the greater difficulty with conflict and suboptimal problems reflect greater reliance on inhibitory processes.

Returning to Conway and Engle (1994), they suggest that individuals have a limited amount of attentional resources to execute both working memory and inhibition processes. They found that when placed in a nonconflict situation, subjects were more likely to be able to execute working memory operations than when placed in conflict situations. Those individuals with the resources available for both inhibition and working memory were successful. It may be that in the 6-move problems, the overall processing resources available for working memory and inhibition were tapped to such an extent that performance suffered.

A more general issue that is often overlooked is the dependent measure used to assess TOL performance. Some researchers use excess number of moves and others use total number of problems correct. Using excess moves may be flawed because although some incorrect moves can be easily corrected with one or two additional moves (e.g., suboptimal problems), others require a complete reversal of the problem that could result in multiple extra moves. For example, a situation could arise in which individual 1 performs well on problems that do not have multiple suboptimal solution paths but cannot inhibit suboptimal moves resulting in incorrect accuracy, but a low number of excess moves. This is in contrast to individual 2 who is able to accurately solve the suboptimal problems but may miss one nonconflict problem that requires a complete reversal. Looking at excess moves in this example may lead one to believe that individual 2 has poorer performance on the task than individual 1. Therefore, looking at excess moves could be very misleading. For these reasons, it is important to consider the operational definition of performance when conducting and evaluating performance on the Tower of London.

There are several methodological issues that should be addressed in future research. First of all, the overall accuracy on this version of the Tower of London was low, only 48%. Welsh et al. (1999) found an accuracy of 59% using a similar version of the Tower of London that included 4, 5, and 6-move problems. Because the problem structure affected performance along with increasing the number of moves, it may be that this task was more difficult or that the inclusion of 4-move problems raised accuracy in the Welsh et al. Tower of London version. Another possibility is that the lower accuracy could be due to testing conditions. Welsh et al. used manual one-on-one testing whereas the current study used a computerized version of the Tower of London. Future studies should also include more problems in each of the conditions to increase the power of the results.

Overall, these findings indicate that the underlying structure of Tower of London problems contributes to overall accuracy, and global performance may miss deficits associated with a particular type of problem. In addition to difficulties in comparing different versions of the Tower of London, it is now apparent that even within the same 3-peg version of the task, the specific problems used can affect results. It remains unclear, however, how different types of problems affect the recruitment of working memory and inhibitory processes.

CHAPTER V

EXPERIMENT 3

Experiments 1 and 2 both revealed that working memory did not significantly contribute to Tower of London performance, a surprising finding in light of suggestions that working memory is critical to performance (Welsh et al., 1999; Cohen, 1996). Most existing studies on this topic have adopted the approach used in Experiments 1 and 2, using regression analyses to estimate the contributions of various cognitive processes to Tower performance. Given the various problems inherent in correlational approaches and the inconsistencies found in the literature, a new methodology is needed for examining the role of inhibition and working memory in Tower of London performance. Therefore, this experiment will use dual-task methodology to assess the contribution of working memory to Tower of London performance. Phillips et al. (1999) adopted this approach in a recent study, but they employed rather complex secondary tasks that may have been tapping into multiple cognitive processes. The present study will use a basic, working memory maintenance task as the secondary task.

In a dual-task study, performance while doing one task is compared to performance doing two tasks. If performance with two tasks results in a decrement in performance on one task, then it can be concluded that the tasks use overlapping or similar resources. However, if performance with two tasks does not differ substantially from performance of one alone, then it can be concluded that the cognitive processes in the two tasks may not be strongly related. By systematically varying the working memory load using a modified version of the Sternberg Item Recognition Task (Sternberg, 1969), the role of working memory in solving the Tower of London can be examined. It is important to note that researchers often assume that increasing the number of moves adds to the complexity of the Tower task and makes additional demands on working memory (e.g., Unterrainer et al., 2004). Yet Zook, Welsh and Ewing (in press) found that across age groups, there was not a significant decline in performance from the 5- to 6-move Tower of London items, even in light of the fact that another move had to presumably be planned in working memory. Using dual-task methodology, it is possible to examine the role of working memory in Tower performance how it relates to additional moves needed to solve Tower of London problems.

Cohen (1996) stressed the importance of working memory in Tower of London performance, arguing that it is important for formulating, retaining, and implementing plans. In addition, the need to revise plans ‘on-line’ would presumably require working memory, as well. Phillips, Gilhooly, Della Salla, and Logie (1999) examined working memory and the Tower of London in a variety of dual-task situations. They argue that setting up, maintaining and executing a plan in a Tower of London problem most likely makes demands on working memory. They found that both verbal and visuospatial working memory tasks resulted in a decrease in performance on the Tower of London. In a more recent study using an individual differences approach, Gilhooly, Wynn, Phillips, and Della Salla (2002) concluded that the Tower of London reflects visuo-spatial, and not verbal, working memory functions. In contrast, using a three-peg version of the Tower, Unterrainer et al. (2004) found that visuo-spatial working memory tasks did not predict or correlate with Tower performance and in fact found a tendency, though non-significant, for verbal working memory to correspond to performance. Thus, existing dual-task studies are inconsistent with regard to the contribution of working memory to Tower of London performance, even among studies that used that same version of the task (i.e., Phillips et al. & Gilhooly et al.).

There are several concerns with the studies by Phillips et al. (1999) and Gilhooly et al. (2002). First of all, the Tower of London used by Phillips et al. does not impose as many limitations as other common versions of the Tower of London. Phillips et al. used five-disc tower problems (see Ward & Allport, 1997) with all of the pegs of equal height, whereas many Tower tasks use three pegs of varying heights, where one peg can hold three balls, one can hold two, and one can hold three. Berg and Byrd (2002) argue that the five-disk version of the Tower task, as used by Phillips et al., changes not only the spatial characteristics of the problem space, but may also change the underlying cognitive processes that are used to complete the task. They point out that the five-disk version does not have the same restrictions based on size that is fundamental in other versions of the Tower of London nor does it have the size placement restriction imposed by another disk transfer task, the Tower of Hanoi. Because the task does not have these restrictions, participants no longer have to remember a rule that guides performance. Phillips et al. also used a within-subjects design such that each participant completed three versions of the Tower task, the control condition and two dual-task conditions. This is problematic for a study that attempts to examine EF, because by definition EF performance relies on novelty. Finally, the Tower problems used by Phillips et al. were solved using a light pen on a PC monitor, thereby adding a motor component to the task that may have affected the response time results.

The present study uses a dual-task paradigm to assess the role of working memory maintenance in Tower performance, while addressing concerns with the work by Phillips et al. (1999). Three-peg Tower problems will be given to increase the constraints on possible solutions. In addition, a verification paradigm (Carder et al., 2004) will be employed, such that a move will be shown to the participant and they must verify if it is or is not the correct move. This paradigm allows for the examination of response time at the level of each individual move and removes possible influences of individual differences in motor speed. A modified version of the Sternberg Item Recognition Task (Sternberg, 1966) will be used to assess working memory maintenance while solving the problem. The Sternberg Item Recognition Task consists of an encoding phase, in which participants view a string of letters that they are asked remember, followed by a maintenance period, then a final stage in which they are presented with a probe and asked whether the or not the probe was presented in the original string.

By comparing performance of the Tower of London with varying degrees of working memory load in a secondary task, it will be possible to examine the specific role that working memory maintenance plays in performance on the Tower of London. It is predicted that as the secondary task becomes more complex, performance on the primary task (i.e., the Tower of London) will decline due to a decreased amount of resources available or due to the overlap that exists between working memory maintenance resources and the executive resources needed to solve the problem. An interaction between secondary task load and number of required moves is also expected.

Method

Participants

Fifty-two college students (23 females, 29 males; mean age = 20, *SD*=2; range = 18-28) participated in this study in partial fulfillment of the requirements of an introductory psychology course. Participants filled out a consent form and a demographic questionnaire that included age, date of birth, educational history, and medical history in order to screen for serious head injuries or illness that may interfere with performance. No participants were excluded based on these criteria.

Tasks and Procedure

Participants were tested on personal computers. Participants were asked to complete two tasks (described below) simultaneously. First, they were asked to hold one, six, or eight letters in their memory, then they were asked to plan and complete a problem, and this was followed by a question regarding the letters initially presented. Due to the complexity of the task, participants were given a brief PowerPoint presentation outlining the task and were shown a sample problem prior to the start of the task. They were also given two practice problems. An illustration of the process appears in Figure 5.1.

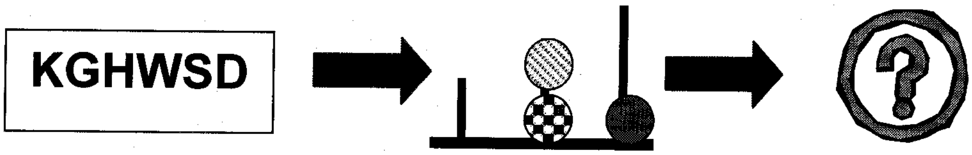

Figure 5.1. Sample illustration of dual task order.

Tower of London-Revised. A computerized version of the Tower of London was given, using problems from the Tower of London-revised (Schnirman et al., 1998) as well as 24 new problems[3]. The objective of the Tower of London-R task is for the participant to reconfigure three different-colored balls on three pegs of different heights. Using pegs of different heights constrains the number of balls that may be placed on each peg (i.e., the smallest peg can fit only one ball, the middle peg can hold up to two balls, and the tallest peg can hold all three balls). In addition, only one ball may be moved at a time and the balls must always be held on one of the three pegs during the move sequence. Participants are told that they must transform the start configuration into the goal state in a predetermined number of moves while adhering to these rules.

Participants were presented 24 problems needing 3 moves and 24 problems needing 5 moves, given in random order within each set. Participants were told the number of moves required for the solution of each problem. The start state and goal state were presented for 8 seconds. After they were given 8 seconds to view the problem, the first move was flashed for 4 seconds on the screen and the participant identified (by key press) whether they believed the move was correct or incorrect. For the 24 problems of each type (i.e., 3- or 5-move problems), 12 involved the presentation of the correct move and 12 involved the presentation of an incorrect move. Performance on the Tower was measured by whether the move was correctly identified as being right or wrong. The time taken to respond to the question was also recorded.

Modified Sternberg Item Recognition Task (SIRT). Participants were also asked to complete a version of the Sternberg task in which working memory load was variable. They were instructed to view and encode a letter string presented in the center of the

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[3] It was necessary to develop twenty-four new 3–move problems and fourteen new 5-move problems.

screen into memory. They were then told that they would need to answer a question regarding the letter string at the end of each trial. In the control condition, a single letter was presented. In the experimental condition, six or eight letters were presented. The letters in both conditions were presented for 5 seconds. After completing the Tower of London problem, participants were asked whether the letter shown was one of the letters presented at the start of the trial. Participants were given 10 seconds to answer the question. The measures used were accuracy and response time on the correct trials.

Results

All of the means and standard deviations (accuracy and response time) for the Tower of London and SIRT task are located in Appendix V. Two participants were excluded from the study. One participant was excluded based on low accuracy (8 of 48 problems correct), which was more than two standard deviations below the mean of 28.27 (*SD* = 6.26). Another participant was excluded because they failed to make a response on 14 consecutive items. Two of the 3-move problems were dropped from the analyses based on programming errors that made them unsolvable. The alpha level for all analyses was set at $p < .05$.

Reliability Analysis

A Cronbach's alpha internal consistency reliability analysis was conducted in order to determine if reliability of the Tower of London was maintained in a dual-task situation. The reliability analysis revealed a moderate Cronbach alpha, Alpha = .67. Inter-item correlation coefficients are located in Appendix V.

Sternberg Item Recognition Task

Accuracy. A 2 (number of moves) x 3 (number of letters) repeated measures ANOVA was conducted in order to identify whether there were significant differences in accuracy on the SIRT as the number of TOL moves and number of SIRT letters increased. There was not a significant main effect for number of moves (*M*s = .88 and .86 for the three- and five-move problems, respectively). However, there was a significant main effect for number of letters [$F(2, 102) = 13.29, p < .05, MSE = .021$, partial $\eta^2 = .20$; See Figure 5.2], with contrasts indicating that 1 and 6 letter accuracy did not differ (*Ms* = .90 and .89 respectively). There was a significant decline in accuracy in the 8 letter condition ($M = .81$) from both the 1 letter [$F(1, 51) = 16.96, p < .05, MSE = .014$, partial $\eta^2 = .25$] and 6 letter conditions [$F(1, 51) = 24.64, p < .05, MSE = .011$, partial $\eta^2 = .32$]. There was also a significant interaction between number of moves and number of letters, $F(2, 102) = 7.452, p= .001, MSE = .012$, partial $\eta^2 = .13$.

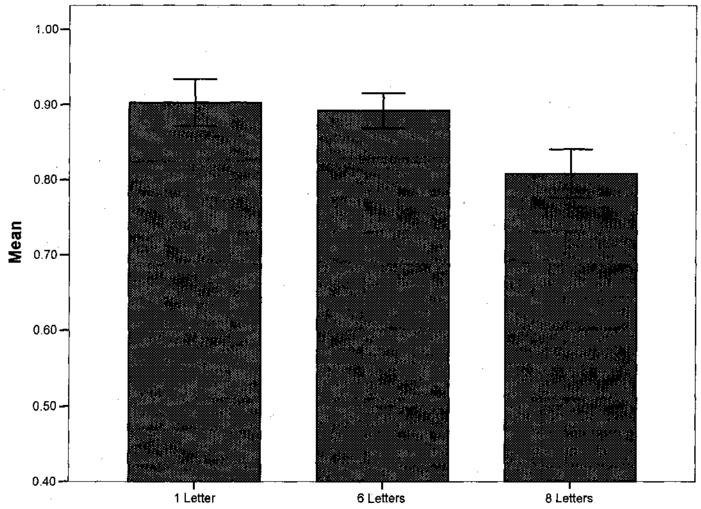

Figure 5.2. Proportion correct on the TOL problems as a function of number of letters.

A repeated measures ANOVA was conducted examining accuracy on the letter task for 3-move TOL problems. A significant difference between number of letters was found [*F*(2, 102) = 3.82, $p < .05$, *MSE* = .013, partial $\eta^2 = .07$; see Figure 5.3]. Contrasts indicated no significant difference between 1 and 6 letters or 1 and 8 letters, but there was a significant difference between 6 and 8 letters [*F*(1, 51) = 10.2, $p < .05$, *MSE* = .02, partial $\eta^2 = .17$] with the proportion of correct responses being higher for 6 letters (*M* = .91) than 8 letters (*M* = .85).

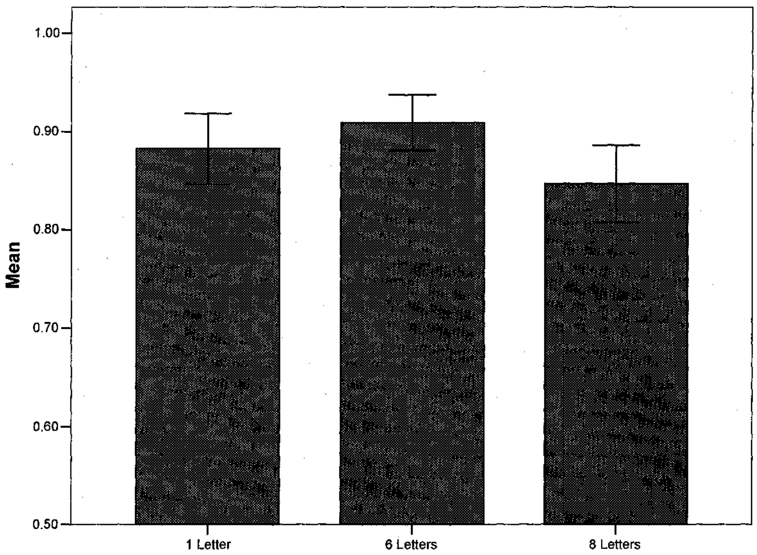

Figure 5.3 . SIRT accuracy as a function of number of letters with 3-move TOL problems.

For 5-move TOL problems, there was also a significant difference between the letter conditions [*F*(2, 102) = 16.00, $p < .05$, *MSE* = .020, partial $\eta^2 = .24$]. Contrasts indicated that the difference between 1 letter and 6 letters was not significant. However, the difference between 1 and 8 letters was significant [*F*(1, 51) = 25.55, $p < .05$, *MSE* = .048, partial $\eta^2 = .33$] with the proportion of correct answers being higher in the 1 letter condition (*M* = .92) than in the 8 letter condition (*M* = .77). The difference between 6 and 8 letters was also significant [*F*(1, 51) = 18.48, $p < .05$, *MSE* = .031, partial $\eta^2 = .26$; see

Figure 5.4] with the proportion of correct responses being higher for 6 letters (*M* = .88) than 8 letters (*M* = .77).

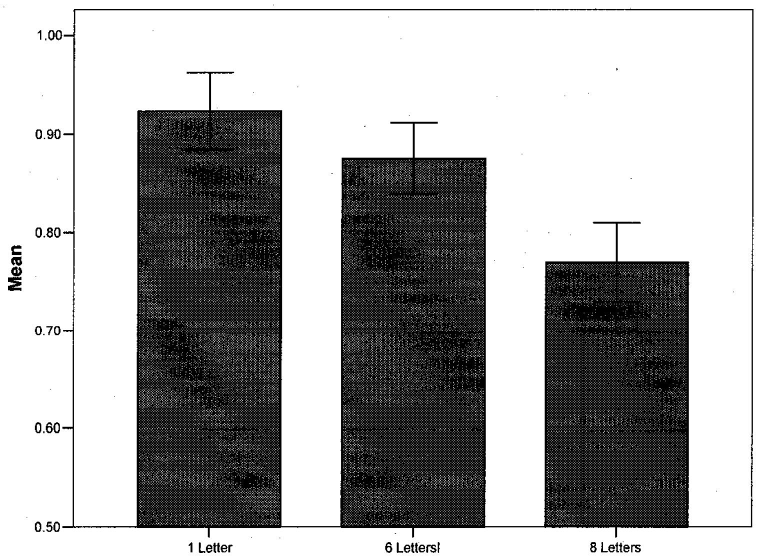

Figure 5.4. SIRT accuracy as a function of number of letters with 5-move TOL problems.

Response Time. Response times (in ms) for correct responses on the SIRT verification task were analyzed using a 2 (number of moves) x 3 (number of letters) repeated measures ANOVA in order to determine whether there were significant differences in response time as the number of TOL moves and number of SIRT letters increased. There was a significant main effect for number of moves [$F(1, 51) = 23.16$, $p < .05$, $MSE = 147819.43$, partial $\eta^2 = .31$] with faster SIRT responses for 5-move problems ($M = 1371$) than 3-move problems ($M = 1581$). There was also a significant main effect for the number of letters [$F(2, 102) = 69.40$, $p < .05$, $MSE = 75286.25$, partial $\eta^2 = .58$] with 1-letter problems being solved the fastest ($M = 1262$ ms) followed by 6-letter problems ($M = 1457$ ms) and 8-letter problems ($M = 1709$ ms). The interaction between type of move and number of letters was also significant [$F(2, 102) = 9.27, p < .05$, $MSE = 86518.51$, partial $\eta^2 = .15$].

For 3-move TOL problems, there was an effect of number of letters [$F(2, 102) = 27.46, p < .05$, $MSE = 92613.66$, partial $\eta^2 = .35$; see Figure 5.5]. Contrasts indicated no significant difference between 1 and 6 letters. However a difference was found between 1 and 8 letters [$F(1, 51) = 38.94, p < .05$, $MSE = 207574.88$, partial $\eta^2 = .43$] with 1-letter problems ($M = 1441$) being solved faster than 8-letter problems ($M = 1836$). A significant difference between 6 and 8 letters [$F(1, 51) = 42.29, p < .05$, $MSE = 168935.66$, partial $\eta^2 = .45$] was also found with 6-letter problems ($M = 1465$) being solved faster than 8 letter problems.

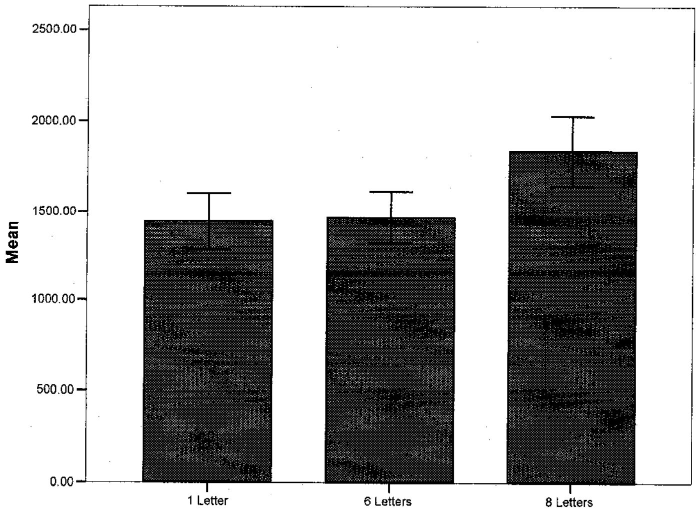

Figure 5.5. Mean response time to SIRT letter task for 3-move TOL problems; error bars represent 95% confidence intervals.

For 5-move TOL problems, an effect of number of letters was also observed, [$F(2, 102) = 50.36, p < .05$, $MSE = 69191.11$, partial $\eta^2 = .50$; see Figure 5.6]. Contrasts showed a significant difference between all three conditions: 1 vs. 6, [$F(1, 51) = 68.57, p < .05$, $MSE = 101901.44$, partial $\eta^2 = .57$]; 1 vs. 8, [$F(1, 51) = 91.48, p < .05$, $MSE =$

142051.33, partial $\eta^2 = .64$]; and 6 vs. 8, [$F(1, 51) = 5.4, p < .05$, $MSE = 171193.88$, partial $\eta^2 = .10$], with 1 letter ($M = 1083$) being solved the fastest, followed by 6 letters ($M = 1449$) and finally 8 letters ($M = 1582$).

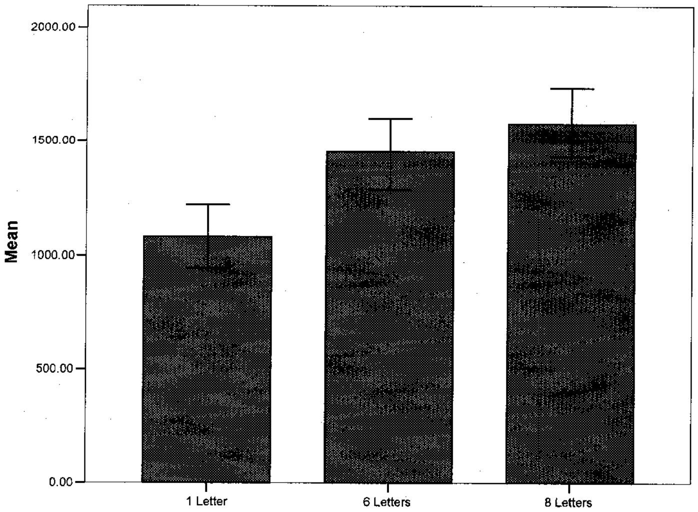

Figure 5.6. Mean response time to SIRT letter task for 5-move TOL problems; error bars represent 95% confidence intervals.

Tower of London

Accuracy. In order to address the question of whether the working memory load affects Tower of London accuracy at each of the move levels, a 2 (number of TOL moves needed to solve the problem) x 3 (number of SIRT letters presented) repeated measures analysis of variance (ANOVA) was conducted. There was a significant main effect of number of moves [$F(1, 51) = 162.38$, $p < .05$, $MSE = .026$, partial $\eta^2 = .76$] indicating that the 3-move condition ($M = .76$) had higher accuracy than the 5-move condition ($M = .52$; see Figure 5.7). Accuracy in the 5-move condition was not different from chance. There was also a main effect for the number of letters presented [$F(2, 102) = 13.70$, $p < .05$, $MSE .= 017$, partial $\eta^2 = .21$] showing that more letters in the secondary task reduced performance (see Figure 5.8). Contrasts indicate significant differences between proportion of problems solved correctly with 1 ($M = .65$) versus 6 letters ($M = .68$) [F(1,

51) = 11.30, $p < .05$, *MSE* = .008, partial $\eta^2 = .18$] as well as between 6 and 8 letters (*M* = .59) [$F(1, 51) = 16.02$, $p < .05$, *MSE* = .009, partial $\eta^2 = .24$]. The difference between 1 and 8 letters approached but did not reach significance [$F(1, 51) = 3.82$, $p < .10$, *MSE* = .007, partial $\eta^2 = .07$]. There was not a significant interaction between number of moves and number of letters.

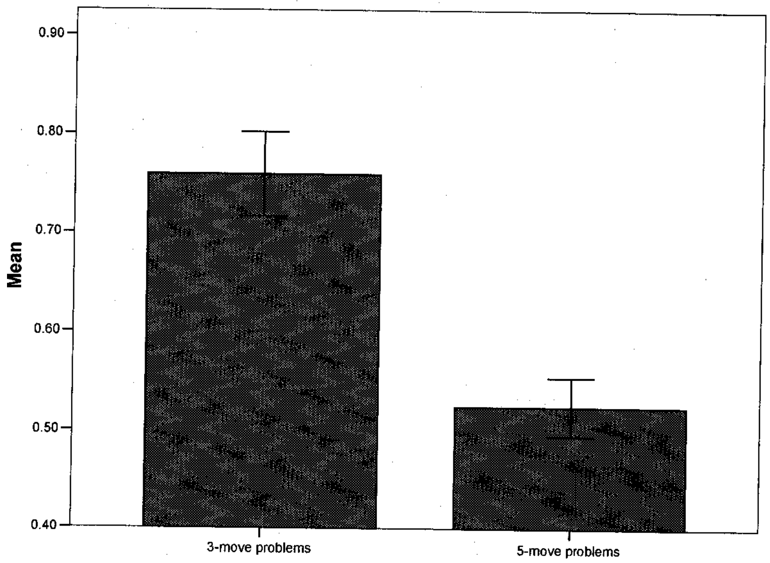

Figure 5.7. Proportion correct on 3-move versus 5-move problems; error bars represent 95% confidence intervals.

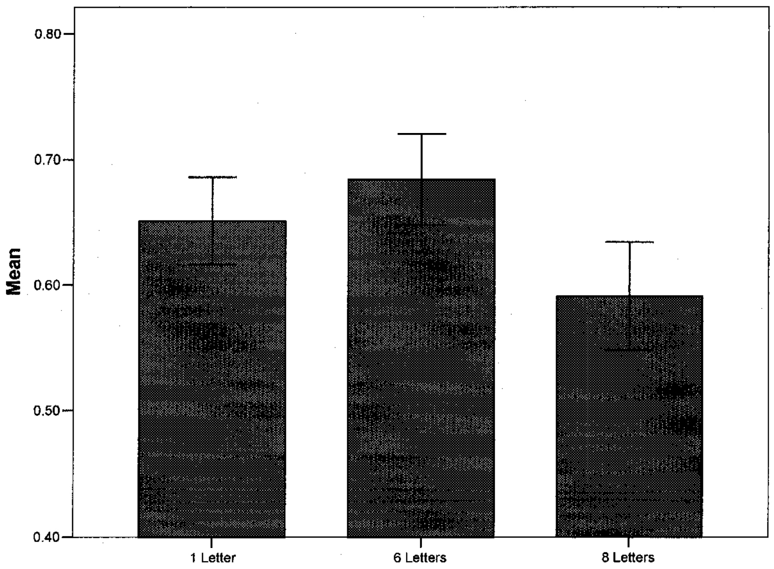

Figure 5.8. Proportion correct across all of the problems as a function of number of letters.

Response Time. Response times (in ms) for correct responses on the TOL verification task were also analyzed using a 2 (number of moves) x 3 (number of letters) repeated measures ANOVA. This was conducted in order to identify whether there were significant differences in response time as the number of moves and number of letters increased. There was a significant main effect for number of moves [$F(1, 51) = 13.76$, p $< .05$, $MSE = 312363.14$., partial $\eta^2 = .21$] with the average response time in the 3-move problems ($M = 1786.25$) being faster than the 5-move problems ($M = 2020.97$). There was not a significant main effect for the number of letters. However, the interaction was significant [$F(2, 102) = 4.22, p < .05, MSE = 139640.75$, partial $\eta^2 = .08$]. In the 3-move problems, there was an effect of number of letters [$F(2, 102) = 4.79, p < .05, MSE = 148199.88$., partial $\eta^2 = .09$]. Contrasts indicated significant differences between 1 and 6 letters [$F(1, 51) = 11.13, p < .05, MSE = 254666.77$, partial $\eta^2 = .18$] with response times faster in the 6 letter condition ($M = 1671.18$ vs. 1904.70). There was not a significant difference between response time in the 6 and 8 letter condition or between 1 and 8 letters. In the 5-move problems, there were no significant differences in response time across the 3 conditions.

Discussion

As stated previously, past literature is inconsistent as to the role of working memory in the Tower of London. Although some studies show a relationship between working memory and Tower of London performance (e.g. Cohen, 1996; Gilhooly, Wynn, Phillips, and Della Salla, 2002; Welsh et al. 1999) other studies have found little support for this relationship (e.g. Lehto, 1996, Ward & Allport, 1997). Kane and Engle (2002) suggest that "the capability to maintain a memory representation in an active state despite distractions, and in interference-rich contexts, is precisely the aspect of executive attention that is critical to predicting general success across higher order cognitive domains (p.660)". By comparing performance of the Tower of London with varying degrees of working memory load in a secondary task, this study sought to examine the specific role that working memory maintenance plays in performance on the Tower of London. It was predicted that as the secondary task became more complex, performance on the primary task (i.e., the Tower of London) would decline due to a decreased amount of resources available or due to the overlap that exists between working memory maintenance resources and the executive resources needed to solve the problem. This would be especially apparent in the 5-move condition when working memory is required to hold five moves online as well as the letters.

Looking first at performance on the SIRT task, it appears that the manipulation of number of letters was successful in increasing working memory load. The general pattern observed was that as the number of letters increased, accuracy on the SIRT task was reduced and response time was slowed. Turning to the effect that this increase in working memory load had on TOL performance, we see that as the working memory load on the SIRT task increased, TOL performance decreased from 1 letter to 8 letters. This set of results suggests that the TOL does place significant demands on the maintenance of information in working memory.

Contrary to what was predicted, however, the pattern of performance as a function of number of letters did not differ for the 3- and 5-move problems. Although overall accuracy on the 5-move problems was lower than in the 3-move condition, the expected interaction between move number and number of letters was not found. Previous researchers have suggested that as the number of moves needed to solve the problem increases, there are additional working memory requirements which make the problem more difficult to solve (e.g. Unterrainer et al., 2004). The lack of an interaction in this study suggests that the demands on maintained information in working memory maintenance is not related to the number of moves required, at least across the range of problems used here.

One interesting trend in the data was that TOL performance did not systematically decline as more letters were added, but seemed to reach a critical point at which participants struggled to accurately identify correct moves. This pattern of results may indicate that rather than systematically affecting performance when more letters are added, aspects of working memory may work on an all or nothing principle. In other words, performance on the primary task may only affected by the secondary task when working memory maintenance is at its maximum point.

There were some methodological issues that should be addressed in future research. The low accuracy in the 5-move Tower of London problems could be due to the timing of the task. The time that the Tower problem was shown was identical in the 3-move and 5-move condition. It may be necessary to extend the time in the 5-move condition in order to improve the accuracy score. It may also be worthwhile to add a fourth condition in which participants are not asked to maintain any letters in working memory. Such a condition may give further insight into the role of working memory maintenance and performance on the task. Finally, although participants were asked to do their best on both tasks, it may be that they focused on the letter task more than the Tower task. Responses to questions given after the experiment showed that the majority of participants tried the hardest on the letter task.

Future studies should examine the SIRT task in a variety of conditions, looking at both verbal and visuo-spatial maintenance tasks. Although there has been support for the role of visuo-spatial working memory in the Tower of London task (Gilhooly et al., 2002; Phillips et al., 1999; & Welsh et al., 1999) and support for the role of verbal working (Unterrainer et al., 2004), there is a remarkable amount of inconsistency across studies regarding which *type* of working memory underlies performance on the task. Using multiple versions of the SIRT task presents a promising way to systematically alter the type of working memory maintenance as well as the type of working memory (i.e., maintenance vs. active manipulation) while keeping the basic form of the task the same.

CHAPTER VI

GENERAL DISCUSSION

Summary of Experiments

The aim of the three experiments presented here was to examine the underlying component processes involved in the Tower of London with specific emphasis on the role of working memory and inhibition in task performance. An additional goal was to identify whether characteristics at the individual problem level affect which cognitive resources are recruited. The results found in these experiments raise important theoretical questions about the component processes involved in Tower of London performance.

Experiment 1 examined the contributions of working memory, inhibition, and fluid intelligence to executive function performance as measured by the Tower of Hanoi and Tower of London tasks. Results revealed that working memory and inhibition composite measures accounted for a significant amount of variance on the Tower of Hanoi, but neither accounted for a significant amount of variance on the Tower of London. When looking at the contribution of working memory, the results, across individual measures (Visual Span and Memory Cards), indicated that working memory significantly contributed to Tower of Hanoi but not Tower of London performance. When examining inhibitory processes, the results indicated that while one inhibition measure (CCS perseverative errors) significantly contributed to Tower of Hanoi and not to Tower of London performance, the second inhibition measure (Stroop interference) significantly contributed to Tower of London but not Tower of Hanoi performance. These results suggest that even though the two tasks are generally thought to reflect similar cognitive processes, this may not be the case. The tasks may recruit different levels of the same processes or even different processes all together. Another finding was that fluid intelligence was the primary predictor of performance on the Tower of London, whereas fluid intelligence, working memory, and inhibition were all significant predictors of performance on the Tower of Hanoi.

Experiment 2 addressed the question of whether or not the structure of Tower of London problems affect the cognitive processes recruited. It was hypothesized that problems with conflict moves or alternative suboptimal solution paths would be more difficult and that based on their structure they would recruit more inhibitory processes than other Tower of London problems. It was also thought that examining global performance on the TOL task would mask or dilute the contributions of working memory and inhibition to this specific subset of problems. The results showed that at least with 6-move TOL problems, conflict and subotpimal solution problems were more difficult than nonconflict problems. However, contrary to expectations, the inhibition composite and the combined working memory/inhibition composite explained more variance in overall Tower of London and nonconflict move performance than suboptimal and conflict problem performance.

Experiment 3 compared Tower of London performance with varying degrees of working memory load. The goal of this study was to examine the specific role that working memory maintenance plays in performance on the Tower of London using dual-task methodology. It was hypothesized that as working memory maintenance increased, performance on the Tower of London would decline due to an overlap or limitation of available resources. Furthermore, it was predicted that this would be more apparent on 5-move TOL problems than 3-move TOL problems, based on the widely held view that more moves demand more working memory resources. Overall, performance on the TOL did decline as the maintenance requirements of the working memory increased (e.g., in going from the 6-letter to 8-letter condition of the working memory task). However, contrary to predictions, a similar pattern was obtained for 3- and 5-move TOL problems, suggesting that the 5-move TOL problems did not require more resources for the maintenance of information in working memory. Also note that although the highest working memory maintenance load (8 letters) yielded the lowest level of accuracy on the TOL, the 6-letter condition was not different from the baseline (1 letter) condition. This decline did not seem to systematically vary as more letters were added, but in fact seemed to reach a capacity or threshold at which point participants were essentially no longer able to complete the task above the level of chance.

The Role of Working Memory and Inhibition in Tower of London Performance

The studies undertaken here do not uniformly support the view that performance on the Tower of London can be conceptualized in terms of working memory and inhibition. As stated previously, there is a remarkable lack of consistency when examining the role of working memory and inhibition in this task. These inconsistencies need to be acknowledged and the theoretical assumption that these two processes underlie performance on the Tower of London should be questioned.

With these difficulties in mind, dual-task methodology such as that used in Experiment 3 may provide better insight into the role of working memory maintenance in

Tower of London performance. The current study suggests that performance is not affected by working memory maintenance until the point in time that capacity is reached. Thus, individual differences in working memory may not affect Tower performance on less complex problems. More complex problems may require a higher capacity of working memory and at this point some participants may lack the resources needed to successfully or efficiently solve the problem. Additional research is needed to further examine this possibility and to examine whether or not the effects of different forms of working memory (i.e., manipulation vs. maintenance or verbal vs. visuo-spatial) on Tower of London performance.

As advances in neuroimaging and neuroscience are made, it is also vital to relate behavioral processes to cortical organization. Multiple neuroimaging studies have found that the prefrontal cortex is active on Tower of London tasks (see Dagher et al., 1999; Lazeron et al., 2000), working memory tasks (see Cairo, Liddle, Woodward & Ngan, 2004; D'Esposito, Postle & Rypma, 2000) and inhibition tasks (see Knight, Staines, Swick & Chao, 1999). Carpenter, Just and Reichle (2000) point out that the idea that each function is localized to a single, specific area needs to be reconsidered. In support of this, they hypothesize that "if small cortical regions may participate in more than one function, then there may be some overlap between entire large-scale networks subserving different processes"(p. 197). Therefore, one-to-one mapping of function and cortical area is not really possible and what we should now focus on investigating the interactions between the processes that must be coordinated in Tower of London performance. More importantly, the question of how (and how much) cognitive resources are allocated to a specific task, why they are recruited, and which are recruited becomes central to understanding cognition. Thus, looking at the elements of cognition, in this case exploring working memory and inhibition as component processes underlying performance on the Tower of London, can only offer a glimpse into the complexities of the underlying neural networks.

Another important issue pertains to the dependent measure that is used to assess Tower of London performance. Sometimes performance is defined in terms of excess number of moves and other times in terms of total number of problems correct. Using excess moves may be misleading because on some problems incorrect moves can be easily corrected with one or two additional moves (e.g., suboptimal problems), but others require a complete reversal of the problem, which could result in many more extra moves. Given the results of Experiment 2 indicating that performance differs based on the type of problem, data from Experiment 1 were reanalyzed using the total number correct rather than excess moves. Comparing the regression analyses using excess moves first and then the reanalysis using the total number correct, the variance accounted for changed from 0 to 2% in the case of the working memory composite, from 5% to 2% in the case of the inhibition composite, and from 5% to 4% in the case of the combined working memory/inhibition composite. Looking at fluid intelligence, the amount variance explained remained the same at 16%. Although the amount of variance explained by fluid intelligence did not change and the variance explained by working memory and inhibition did not change substantially, the differences in results based on the performance measured used should still be noted.

Tower of London and EF

A more general question is whether or not performance on the Tower of London is a good measure of EF. As previously noted, the Tower of London is widely used as an EF task based on its ability to discriminate patients with frontal lobe damage from others, based on research indicating that the prefrontal cortex is active during performance and theoretically because it is thought to be a novel task involving goal-oriented planning. Given this evidence of construct validity, many argue that the Tower of London captures much of what is meant by EF.

Welsh et al. (in press) suggest, however, that EF "is not any single cognitive process (e.g., working memory), but the coordination of more than one cognitive process (e.g., working memory and inhibition, allowing for flexible, strategic action)". Carrying this further, if it is the coordination aspect that is relevant to the study EF, is it possible to separate out and measure component processes? Are individual differences in performance reflective of varying abilities pertaining to the component process or of coordinating these skills? According to Hughes and Graham (2000), attempting to fractionate EF may over- or underestimate the contributions of cognitive processes depending on the nature of the task. It may be that working memory and inhibition do not "explain" performance any more than other processes such as the ability to visualize the problems or execute the motor sequence necessary to solve the task.

Although working memory and inhibition may be necessary for performing an EF task such as the Tower of London, the idea that they are the primary component processes underlying performance was not supported. Given the multiple measures of EF and the lack of a consistent relationship with purported measures of component processes, it may be that EF needs to be reconceptualized as an executive coordinator. Viewing the executive as a coordinator rather than a set of functions or cognitive processes may explain many of the inconsistencies found in EF research. These inconsistencies may reflect differing degrees of overlap between the cognitive processes recruited at a specific time for a specific task, even while the executive "coordinator" plays a consistent role across tasks. .

Another possibility is that EF is strongly related to fluid intelligence, as suggested by the findings of Experiment 1 in which fluid intelligence explained significant variance in Tower of London performance. Several researchers have suggested that tasks that tap into executive function and fluid intelligence are linked (e.g., Duncan et al., 1995; Pennington et al., 1996). Duncan (1995) asserts that fluid intelligence tasks may be the best measures of executive functioning. Duncan, Emslie and William's (1996) goal neglect studies led to the proposal that *g* is a reflection of controlled processing in the frontal lobes. From a cognitive point of view, both intelligence and EF are thought to reflect high-level executive or supervisory functions (Luria, 1966; Norman & Shallice, 1980). However it is important to note that there is not a consensus that EF and fluid intelligence are the same thing. Crinella and Yu (2000) differentiate between *g* and EF by saying that *g* is a construct that looks at individual performance on a variety of cognitive measures whereas EF looks at single subject performance on a single task. They conclude that, "...fluid g, while undoubtedly requiring extensive EF support, is not an exclusive manifestation of EF (p. 316)." Rabbitt (1997) challenges the notion that EF and fluid intelligence reflect identical cognitive processes, stating that the problem of functional description of executive processes is not solved. Part of the problem could be that both

EF and *g* are such global concepts that they encompass too many domains making it nearly impossible to separate the two. Another issue is that *g* is a statistical construct and a variety of tests may load on a single factor, a factor that includes EF but may not mirror it.

Although this debate will not be settled in the immediate future, it is important to acknowledge that current conceptualizations of EF need to be modified in light of both behavioral and neurophysiological findings. The complexity of the prefrontal cortex and the underlying neural networks may not be able to be explained by a single "executive"; it is more likely that executive functions contribute to different situations in different ways. Adcock, Constable, Gore & Goldman-Rakic (2004) suggest that "executive processes may be mediated by interactions between anatomically and functionally distinct systems engaged in performance of component tasks, as opposed to an area or areas dedicated to a generic executive system" (p. 3567). Returning to Stuss and Alexander (2000) and their suggestion that the central supervisory system is the sum of the cognitive processes recruited for achieving a goal rather than a discrete system, the existing literature and the data found here supports this view.

Implications for Future Research

As a result of the research conducted here, there are several promising areas of inquiry for the future. First, the finding that problem structure affects complexity needs further examination. Understanding how different parameters can be altered to systematically vary the cognitive demands may enhance clinical use of tasks such as the Tower of London by allowing clinicians to identify specific deficiencies.

In addition, promising new paradigms such as Carder et al.'s (2004) verification paradigm, when combined with dual-task methodology, allows not only for the systematic variation in working memory load, but also the ability to identify reaction time differences by problem type and memory load. Furthermore, using tasks such as the Sternberg Item Recognition Task, it is possible to look at working memory maintenance, working memory manipulation, verbal working memory and spatial working memory as each relates to a specific type of problem. Such research would allow us to move past trying to identify which component cognitive processes are related to executive function to identifying how each interacts with the specific behavior involved at the level of each individual problem.

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APPENDIX I

Full Pearson correlation matrix for Experiment 1

	Tower of London	Tower of Hanoi	CCS	Stroop	Visual Span	Matrix Reasoning	Memory Cards
Tower of London	--	.271*	.036	.219*	.076	-.402**	-.003
Tower of Hanoi		--	.282*	.183	-.342**	-.389**	.222*
CCS			--	-.064	-.108	-.085	.106
Stroop				--	-.114	-.147	-.022
Visual Span					--	.062	-.384**
Matrix Reasoning						--	-.252*
Memory Cards							--

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

APPENDIX II

Inter-item correlation coefficients for the Tower of London, Experiment 1

Tower of London Problem Number

	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	-.045	-.072	-.067	-.050	.009	-.039	.099	-.039	-.058	-.037	-.032	.064	-.052	.017	.019	.004	-.110	-.102	-.059
3		.170	.089	-.051	-.045	-.040	.143	-.008	-.060	-.038	-.033	-.033	-.047	.397	.112	-.061	-.088	-.030	-.060
4			-.089	-.081	-.072	-.064	.175	-.051	-.096	.001	-.053	.237	.240	.215	.077	-.098	.064	.010	.056
5				.272	-.008	.263	-.016	.386	.040	.018	.052	.055	-.080	.188	.116	-.039	-.060	-.066	.048
6					.051	-.044	.020	.615	-.066	-.042	-.036	-.078	-.023	-.037	.013	-.067	.019	.007	.143
7					--	-.039	-.026	-.030	-.046	-.037	-.032	-.006	-.076	-.052	.032	-.030	.013	.063	-.032
8						--	.294	-.019	.116	-.033	-.004	-.061	-.049	-.057	-.080	.049	.089	-.090	-.052
9							--	-.036	.220	-.053	-.062	.154	.032	.017	-.076	.067	.327	-.108	-.068
10								--	-.052	.013	-.029	.170	-.063	-.076	.078	-.037	-.067	-.063	-.038
11									--	-.049	-.043	.048	-.065	-.053	-.098	.143	.069	-.029	-.039
12										--	-.027	-.059	-.027	-.096	-.007	.026	-.058	-.086	-.050
13											--	-.051	-.059	-.039	.095	-.044	-.053	-.075	-.043
14												--	-.090	.020	.230	.057	-.133	.085	-.027
15													--	-.036	-.009	.155	.105	.122	-.039
16														--	.379	.049	-.054	.163	-.137
17															--	.326	-.106	.141	-.016
18																--	-.034	.009	-.080
19																	--	-.004	-.038
20																		--	-.008

APPENDIX III

Inter-item correlation coefficients for Experiment 2

Tower of London Problem Number

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00	0.22	0.19	-0.26	0.31	0.26	0.19	-0.06	0.01	0.03	-0.02	-0.09	0.25	0.13
2	0.22	1.00	0.08	-0.05	0.50	0.06	0.13	-0.08	0.03	0.00	0.15	0.02	0.13	0.00
3	0.19	0.08	1.00	0.18	0.25	0.12	0.30	-0.08	0.38	0.30	0.25	0.09	0.25	0.21
4	-0.26	-0.05	0.18	1.00	0.01	0.25	0.00	0.15	0.00	0.20	0.14	0.00	-0.11	-0.06
5	0.31	0.50	0.25	0.01	1.00	0.21	0.17	-0.22	-0.02	0.03	-0.13	-0.05	0.00	0.03
6	0.26	0.06	0.12	0.25	0.21	1.00	0.18	0.05	-0.13	0.17	0.09	0.04	0.04	0.08
7	0.19	0.13	0.30	0.00	0.17	0.18	1.00	-0.13	0.13	-0.17	0.08	-0.13	0.32	0.00
8	-0.06	-0.08	-0.08	0.15	-0.22	0.05	-0.13	1.00	0.19	0.11	0.21	0.25	0.17	-0.14
9	0.01	0.03	0.38	0.00	-0.02	-0.13	0.13	0.19	1.00	0.08	0.51	0.12	0.14	0.08
10	0.03	0.00	0.30	0.20	0.03	0.17	-0.17	0.11	0.08	1.00	0.09	0.15	-0.03	0.03
11	-0.02	0.15	0.25	0.14	-0.13	0.09	0.08	0.21	0.51	0.09	1.00	0.12	0.40	0.37
12	-0.09	0.02	0.09	0.00	-0.05	0.04	-0.13	0.25	0.12	0.15	0.12	1.00	0.13	0.33
13	0.25	0.13	0.25	-0.11	0.00	0.04	0.32	0.17	0.14	-0.03	0.40	0.13	1.00	0.34
14	0.13	0.00	0.21	-0.06	0.03	0.08	0.00	-0.14	0.08	0.03	0.37	0.33	0.34	1.00
15	-0.01	-0.12	0.27	0.18	-0.16	0.21	0.04	0.09	0.13	0.39	0.16	0.28	0.06	0.30
16	0.04	0.13	0.34	0.16	0.22	0.04	0.32	0.00	0.23	0.06	-0.09	0.23	0.02	-0.03
17	-0.14	-0.13	0.32	0.11	0.10	0.23	-0.05	0.18	0.30	0.31	0.37	0.53	0.08	0.40
18	-0.06	0.30	0.18	0.23	0.07	-0.03	0.03	0.20	0.19	0.11	0.21	0.16	0.17	-0.06
19	0.24	0.18	0.06	0.09	0.04	-0.02	0.40	-0.07	0.11	0.07	0.23	-0.16	0.21	0.07
20	-0.12	0.15	0.16	-0.04	-0.02	0.09	-0.01	0.21	0.43	0.09	0.34	0.31	0.11	0.09
21	0.19	0.18	0.27	0.00	0.25	0.12	0.13	0.09	0.21	0.12	0.16	0.28	0.25	0.21
22	0.12	-0.15	0.31	0.13	0.13	0.17	0.01	0.05	0.26	0.18	0.23	0.07	-0.01	0.00
23	0.33	0.37	0.46	0.01	0.15	0.09	0.07	0.08	0.15	0.34	0.28	0.14	0.29	0.25
24	0.20	0.24	0.09	-0.01	0.11	0.00	0.32	-0.02	0.40	0.03	0.14	0.08	0.16	0.03

Tower of London Problem Number

	15	16	17	18	19	20	21	22	23	24
1	-0.01	0.04	-0.14	-0.06	0.24	-0.12	0.19	0.12	0.33	0.20
2	-0.12	0.13	-0.13	0.30	0.18	0.15	0.18	-0.15	0.37	0.24
3	0.27	0.34	0.32	0.18	0.06	0.16	0.27	0.31	0.46	0.09
4	0.18	0.16	0.11	0.23	0.09	-0.04	0.00	0.13	0.01	-0.01
5	-0.16	0.22	0.10	0.07	0.04	-0.02	0.25	0.13	0.15	0.11
6	0.21	0.04	0.23	-0.03	-0.02	0.09	0.12	0.17	0.09	0.00
7	0.04	0.32	-0.05	0.03	0.40	-0.01	0.13	0.01	0.07	0.32
8	0.09	0.00	0.18	0.20	-0.07	0.21	0.09	0.05	0.08	-0.02
9	0.13	0.23	0.30	0.19	0.11	0.43	0.21	0.26	0.15	0.40
10	0.39	0.06	0.31	0.11	0.07	0.09	0.12	0.18	0.34	0.03
11	0.16	-0.09	0.37	0.21	0.23	0.34	0.16	0.23	0.28	0.14
12	0.28	0.23	0.53	0.16	-0.16	0.31	0.28	0.07	0.14	0.08
13	0.06	0.02	0.08	0.17	0.21	0.11	0.25	-0.01	0.29	0.16
14	0.30	-0.03	0.40	-0.06	0.07	0.09	0.21	0.00	0.25	0.03
15	1.00	0.15	0.32	0.09	0.06	0.16	0.09	0.03	0.12	0.09
16	0.15	1.00	0.28	0.35	-0.11	0.20	0.25	-0.01	0.11	0.16
17	0.32	0.28	1.00	0.18	-0.21	0.28	0.13	0.20	0.25	0.11
18	0.09	0.35	0.18	1.00	0.02	0.21	0.26	0.05	0.40	0.23
19	0.06	-0.11	-0.21	0.02	1.00	0.13	0.16	0.18	0.05	0.19
20	0.16	0.20	0.28	0.21	0.13	1.00	0.34	0.23	0.19	0.23
21	0.09	0.25	0.13	0.26	0.16	0.34	1.00	0.21	0.38	0.35
22	0.03	-0.01	0.20	0.05	0.18	0.23	0.21	1.00	0.16	0.04
23	0.12	0.11	0.25	0.40	0.05	0.19	0.38	0.16	1.00	0.26
24	0.09	0.16	0.11	0.23	0.19	0.23	0.35	0.04	0.26	1.00

APPENDIX IV

Full Pearson correlation matrix for Experiment 2

	TOL Noncft	TOL Conf.	TOL Subop.	CCS Per.	CCS Error	Stroop	SOPT Error	SOPT T-Out	SOPT Per.	VS Forw.	VS Backw	VS Total
TOL Total	.80**	.80**	.88**	-.42**	-.53**	-.05	-.37**	.11	.27	.12	.21	.22
TOL Noncft	--	.44**	.53**	-.45**	-.51**	.14	-.32*	.06	.25	.05	.24	.19
TOL Conf.		--	.61**	-.33*	-.37**	-.05	-.28	.12	.18	-.01	.12	.06
TOL Subop.			--	-.27	-.41**	-.19	-.32*	.07	.25	.23	.16	.26
CCS Per.				--	.82**	.22	.51**	-.04	-.43**	.17	-.24	-.03
CCS Error					--	.20	.51**	.010	-.46**	.07	-.20	-.07
Stroop						--	.06	.01	-.05	-.15	-.13	-.19
SOPT Error							--	-.05	-.86**	.00	-.26	-.16
SOPT T-Out								--	-.47**	-.03	-.25	-.18
SOPT Per.									--	.02	.36*	.23
VS Forw.										--	.12	.79**
VS Backw											--	.70**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Note: TOL = Tower of London; Noncft = nonconflict problems; Conf. = conflict problems; Subop. = Suboptimal solution problems; CCCS Per. = Colorado Card Sort, Perseverative errors; CCS Error = Colorado Card Sort, Total error; SOPT = Self Ordered Pointing Task; SOPT Error = total number of errors; SOPT per. = Percent correct; SOPT T-out = no response before time ran out; VS = Visual Span; VS Forw. = Forward span; VS Backw = Backward span and VS Total = total span

APPENDIX V

Means and Standard Deviations for Experiment 3

Variable	*M*	*SD*	*Min*	*Max*
Tower of London (3-move) proportion	.7589	.1537	.36	1.00
Proportion correct with 1	.7802	.1843	.43	1.00
Proportion correct with 6	.8125	.1941	.13	1.00
Proportion correct with 8	.6841	.2286	.00	1.00
Tower of London (5-move) proportion	.5248	.1070	.33	.75
Proportion correct with 1	.5216	.1617	.25	.88
Proportion correct with 6	.5553	.1631	.25	.88
Proportion correct with 8	.4976	.1776	.00	.88
Tower of London (3-move) response time	1786.25	454.86	659.38	2781.86
1 letter	1904.70	518.61	849.17	3304.33
6 letters	1671.18	562.29	513.38	3046.67
8 letters	1782.88	576.15	615.60	3796.00
Tower of London (5-move) response time	2020.97	533.84	892.06	3166.07
1 letter	1971.54	598.10	920.17	3274.20
6 letters	2028.75	714.55	577.00	3625.00
8 letters	2062.63	587.75	744.20	3268.75
SIRT (3-move) proportion correct	.8790	.0826	.67	1.00
Proportion correct with 1	.8822	.1296	.50	1.00
Proportion correct with 6	.9087	.1024	.63	1.00
Proportion correct with 8	.8462	.1413	.38	1.00
SIRT (5-move) proportion correct	.8558	.0767	.67	1.00
Proportion correct with 1	.9231	.1403	.50	1.00
Proportion correct with 6	.8750	.1309	.50	1.00
Proportion correct with 8	.7692	.1451	.38	1.00
SIRT (3-move) response time	1581.17	549.58	820.47	3742.45
1 letter	1441.89	575.52	715.29	3067.50
6 letters	1465.48	531.45	688.13	3441.86
8 letters	1836.15	691.13	923.50	4800.67
SIRT (5-move) response time	1371.68	499.44	541.36	3430.73
1 letter	1082.86	503.49	491.25	3117.29
6 letters	1449.43	566.35	541.17	3767.75
8 letters	1582.75	558.96	591.67	3407.17

Note: All response time data is in milliseconds.

APPENDIX VI

Inter-item correlation coefficients for the Tower of London, Experiment 3

Tower of London Problems

	2	3	4	5	6	7	8	9
2	1.00	0.32	0.21	0.14	0.20	-0.10	0.36	0.35
3	0.32	1.00	0.32	0.16	0.27	-0.12	0.08	0.24
4	0.21	0.32	1.00	0.34	0.05	-0.03	0.17	0.46
5	0.14	0.16	0.34	1.00	0.13	0.04	0.24	0.24
6	0.20	0.27	0.05	0.13	1.00	-0.23	-0.03	-0.01
7	-0.10	-0.12	-0.03	0.04	-0.23	1.00	0.29	-0.02
8	0.36	0.08	0.17	0.24	-0.03	0.29	1.00	-0.01
9	0.35	0.24	0.46	0.24	-0.01	-0.02	-0.01	1.00
10	-0.14	0.20	0.01	-0.10	-0.21	0.16	0.04	0.09
11	0.49	0.22	0.09	0.05	-0.07	0.21	0.33	0.35
12	0.23	0.36	0.06	0.09	0.03	-0.24	-0.01	0.31
13	-0.01	0.17	0.27	0.07	0.04	0.05	0.07	0.21
14	0.25	0.04	0.37	0.23	0.11	-0.07	0.14	0.21
15	-0.01	0.06	0.15	0.07	-0.30	0.29	0.19	0.21
16	0.17	0.14	0.27	0.12	-0.16	0.10	0.22	0.55
17	0.04	-0.14	0.07	0.22	0.03	0.29	0.22	-0.19
18	-0.18	-0.21	0.10	-0.09	-0.02	0.23	0.14	0.18
19	0.08	0.00	0.22	0.09	-0.01	0.08	0.09	0.35
21	0.27	0.04	0.04	-0.08	-0.07	0.07	0.35	0.13
22	-0.20	-0.05	0.06	-0.12	-0.17	0.08	-0.12	0.15
23	-0.04	0.04	0.19	0.34	-0.24	0.22	0.34	0.17
24	-0.09	0.00	0.05	0.06	-0.01	0.26	0.06	0.24
25	-0.09	-0.08	0.09	0.07	-0.11	0.20	0.15	0.12
26	0.01	0.00	0.30	0.16	0.19	0.11	-0.01	0.16
27	0.05	-0.04	-0.15	-0.08	-0.15	0.21	0.17	0.04
28	-0.16	0.04	0.30	-0.01	-0.10	0.10	-0.18	0.12
29	0.18	-0.08	0.07	0.04	0.06	0.36	0.22	0.02
30	-0.12	0.04	0.09	-0.05	0.16	-0.02	-0.14	-0.07
31	-0.09	0.04	0.03	-0.05	0.39	0.15	-0.05	0.01
32	0.01	-0.08	-0.03	0.08	-0.29	0.03	-0.01	-0.09
33	-0.12	0.13	-0.09	-0.14	0.07	0.16	0.14	-0.21
34	-0.09	0.12	0.03	-0.13	0.31	-0.09	0.11	-0.11
35	0.01	-0.12	-0.11	0.04	0.17	0.17	0.20	-0.02
36	-0.18	0.04	-0.13	0.18	0.10	-0.02	-0.16	0.00
37	0.16	0.20	0.04	0.01	0.10	0.15	0.01	0.00
38	-0.10	0.12	0.14	0.04	0.09	0.34	0.12	-0.02
39	0.11	0.08	0.24	0.24	-0.04	-0.12	0.24	0.24
40	-0.04	-0.12	0.13	0.33	-0.10	0.02	0.08	0.00
41	0.02	-0.04	-0.05	-0.13	0.00	0.15	0.03	0.13
42	0.08	-0.04	-0.09	0.14	-0.07	-0.14	0.06	0.19
43	0.10	-0.04	0.03	0.13	-0.17	-0.09	0.13	0.15
44	-0.14	0.00	-0.12	0.20	-0.20	0.08	0.01	0.32
45	0.16	0.12	0.12	0.27	0.18	-0.10	0.01	0.26
46	0.11	0.08	0.32	0.16	0.12	0.28	0.08	0.12
47	0.15	0.09	0.22	0.27	-0.02	-0.13	0.27	0.23
48	0.07	0.08	0.02	0.02	0.04	0.30	0.19	0.21

Tower of London Problems

	10	11	12	13	14	15	16	17
2	-0.14	0.49	0.23	-0.01	0.25	-0.01	0.17	0.04
3	0.20	0.22	0.36	0.17	0.04	0.06	0.14	-0.14
4	0.01	0.09	0.06	0.27	0.37	0.15	0.27	0.07
5	-0.10	0.05	0.09	0.07	0.23	0.07	0.12	0.22
6	-0.21	-0.07	0.03	0.04	0.11	-0.30	-0.16	0.03
7	0.16	0.21	-0.24	0.05	-0.07	0.29	0.10	0.29
8	0.04	0.33	-0.01	0.07	0.14	0.19	0.22	0.22
9	0.09	0.35	0.31	0.21	0.21	0.21	0.55	-0.19
10	1.00	0.41	0.02	0.25	-0.04	0.25	0.15	-0.17
11	0.41	1.00	0.09	0.03	-0.03	0.29	0.24	-0.19
12	0.02	0.09	1.00	-0.03	0.09	-0.03	0.26	-0.11
13	0.25	0.03	-0.03	1.00	0.29	0.01	0.21	-0.07
14	-0.04	-0.03	0.09	0.29	1.00	-0.10	0.14	0.03
15	0.25	0.29	-0.03	0.01	-0.10	1.00	0.21	-0.07
16	0.15	0.24	0.26	0.21	0.14	0.21	1.00	-0.15
17	-0.17	-0.19	-0.11	-0.07	0.03	-0.07	-0.15	1.00
18	0.04	-0.12	-0.05	0.30	0.25	0.14	0.17	-0.09
19	-0.09	0.00	0.25	0.31	0.33	0.10	0.20	0.03
21	0.33	0.26	0.22	0.21	0.17	-0.03	0.14	0.04
22	0.20	-0.03	-0.07	0.56	0.21	-0.03	0.26	-0.11
23	0.22	0.22	-0.07	0.12	0.22	0.25	0.19	-0.02
24	0.27	0.35	-0.09	0.21	-0.12	0.21	0.14	-0.10
25	0.31	0.23	0.20	0.19	0.14	0.07	0.02	0.02
26	-0.14	-0.09	0.05	0.08	0.27	0.08	-0.07	0.12
27	0.37	0.47	-0.10	-0.01	0.02	0.10	-0.08	-0.08
28	-0.05	-0.26	-0.01	0.03	0.02	0.03	0.06	0.26
29	-0.08	0.00	0.03	-0.02	0.29	-0.14	0.16	0.16
30	0.04	0.13	-0.09	-0.16	-0.08	-0.03	-0.14	-0.03
31	0.08	0.07	-0.14	-0.04	-0.02	0.18	-0.03	-0.12
32	0.12	0.18	-0.06	-0.27	-0.27	-0.15	-0.07	0.02
33	0.19	0.03	0.03	0.10	0.03	0.10	-0.14	-0.03
34	-0.05	-0.02	0.27	0.07	-0.02	-0.27	-0.22	0.07
35	0.29	0.21	-0.14	0.29	-0.25	0.05	0.10	0.10
36	0.05	-0.12	0.11	-0.27	-0.02	-0.15	-0.06	0.04
37	-0.09	-0.02	0.22	0.09	0.17	-0.15	0.04	0.24
38	0.29	0.21	-0.03	-0.07	-0.07	0.29	0.10	-0.10
39	0.20	0.31	0.05	-0.06	-0.04	0.06	0.24	-0.14
40	-0.05	0.12	-0.22	-0.21	-0.17	0.03	-0.14	0.16
41	0.08	-0.02	0.07	0.18	-0.02	0.18	0.26	0.07
42	0.00	0.16	0.14	-0.09	-0.11	0.02	0.05	-0.23
43	-0.02	-0.12	-0.08	0.30	0.16	0.18	0.20	0.00
44	0.24	0.05	-0.05	0.14	-0.05	0.27	0.22	-0.10
45	-0.09	0.17	0.11	0.09	0.07	0.09	0.24	-0.16
46	-0.20	-0.22	-0.05	0.17	0.04	-0.28	0.05	0.42
47	-0.18	-0.21	0.23	0.19	0.32	-0.08	0.16	0.16
48	0.17	0.18	-0.09	0.14	0.09	0.14	0.29	-0.18

Tower of London Problems

	18	19	21	22	23	24	25	26
2	-0.18	0.08	0.27	-0.20	-0.04	-0.09	-0.09	0.01
3	-0.21	0.00	0.04	-0.05	0.04	0.00	-0.08	0.00
4	0.10	0.22	0.04	0.06	0.19	0.05	0.09	0.30
5	-0.09	0.09	-0.08	-0.12	0.34	0.06	0.07	0.16
6	-0.02	-0.01	-0.07	-0.17	-0.24	-0.01	-0.11	0.19
7	0.23	0.08	0.07	0.08	0.22	0.26	0.20	0.11
8	0.14	0.09	0.35	-0.12	0.34	0.06	0.15	-0.01
9	0.18	0.35	0.13	0.15	0.17	0.24	0.12	0.16
10	0.04	-0.09	0.33	0.20	0.22	0.27	0.31	-0.14
11	-0.12	0.00	0.26	-0.03	0.22	0.35	0.23	-0.09
12	-0.05	0.25	0.22	-0.07	-0.07	-0.09	0.20	0.05
13	0.30	0.31	0.21	0.56	0.12	0.21	0.19	0.08
14	0.25	0.33	0.17	0.21	0.22	-0.12	0.14	0.27
15	0.14	0.10	-0.03	-0.03	0.25	0.21	0.07	0.08
16	0.17	0.20	0.14	0.26	0.19	0.14	0.02	-0.07
17	-0.09	0.03	0.04	-0.11	-0.02	-0.10	0.02	0.12
18	1.00	0.28	0.04	0.23	0.08	-0.09	0.14	0.34
19	0.28	1.00	0.11	0.25	-0.02	-0.06	-0.06	0.23
21	0.04	0.11	1.00	0.11	0.01	0.29	0.27	-0.21
22	0.23	0.25	0.11	1.00	0.16	0.17	0.09	-0.06
23	0.08	-0.02	0.01	0.16	1.00	0.09	0.25	-0.02
24	-0.09	-0.06	0.29	0.17	0.09	1.00	0.27	-0.25
25	0.14	-0.06	0.27	0.09	0.25	0.27	1.00	-0.17
26	0.34	0.23	-0.21	-0.06	-0.02	-0.25	-0.17	1.00
27	-0.06	0.03	0.12	0.10	0.37	0.22	0.17	-0.25
28	0.07	0.05	0.05	0.21	-0.01	-0.07	-0.10	0.21
29	0.41	-0.04	-0.02	-0.08	0.22	-0.13	0.22	0.27
30	0.00	-0.17	-0.17	-0.21	-0.22	0.12	0.05	0.00
31	0.02	0.01	0.07	-0.03	-0.19	0.21	0.19	-0.11
32	-0.10	-0.07	-0.04	-0.16	-0.02	-0.05	-0.01	-0.06
33	0.12	-0.17	0.02	-0.09	0.07	0.12	0.05	0.09
34	0.02	0.01	-0.01	-0.14	-0.10	0.01	0.11	0.21
35	0.01	0.08	0.32	0.29	-0.04	0.26	-0.05	-0.06
36	-0.07	-0.20	0.04	0.01	-0.08	-0.14	0.01	0.05
37	-0.07	0.26	0.13	-0.10	0.01	0.07	-0.08	-0.04
38	0.01	0.08	0.24	0.08	0.05	0.26	0.04	0.03
39	-0.11	0.00	-0.12	0.05	0.38	0.20	-0.08	0.00
40	-0.27	-0.26	-0.13	-0.11	0.08	0.14	0.16	-0.13
41	0.23	0.01	-0.18	0.07	-0.10	0.01	-0.13	0.13
42	-0.03	0.06	0.01	0.14	0.08	0.04	0.06	0.01
43	0.21	0.07	-0.15	0.24	0.04	-0.06	-0.12	0.22
44	0.10	0.15	-0.15	0.07	0.47	0.10	0.01	0.03
45	0.04	0.11	0.04	0.11	0.10	0.07	-0.16	0.13
46	0.11	0.00	0.04	0.05	-0.04	-0.20	0.00	0.32
47	0.27	0.18	0.10	0.11	0.15	-0.11	-0.01	-0.04
48	0.29	0.27	0.15	0.12	0.08	0.19	0.11	-0.18

Tower of London Problems

	27	28	29	30	31	32	33	34
2	0.05	-0.16	0.18	-0.12	-0.09	0.01	-0.12	-0.09
3	-0.04	0.04	-0.08	0.04	0.04	-0.08	0.13	0.12
4	-0.15	0.30	0.07	0.09	0.03	-0.03	-0.09	0.03
5	-0.08	-0.01	0.04	-0.05	-0.05	0.08	-0.14	-0.13
6	-0.15	-0.10	0.06	0.16	0.39	-0.29	0.07	0.31
7	0.21	0.10	0.36	-0.02	0.15	0.03	0.16	-0.09
8	0.17	-0.18	0.22	-0.14	-0.05	-0.01	0.14	0.11
9	0.04	0.12	0.02	-0.07	0.01	-0.09	-0.21	-0.11
10	0.37	-0.05	-0.08	0.04	0.08	0.12	0.19	-0.05
11	0.47	-0.26	0.00	0.13	0.07	0.18	0.03	-0.02
12	-0.10	-0.01	0.03	-0.09	-0.14	-0.06	0.03	0.27
13	-0.01	0.03	-0.02	-0.16	-0.04	-0.27	0.10	0.07
14	0.02	0.02	0.29	-0.08	-0.02	-0.27	0.03	-0.02
15	0.10	0.03	-0.14	-0.03	0.18	-0.15	0.10	-0.27
16	-0.08	0.06	0.16	-0.14	-0.03	-0.07	-0.14	-0.22
17	-0.08	0.26	0.16	-0.03	-0.12	0.02	-0.03	0.07
18	-0.06	0.07	0.41	0.00	0.02	-0.10	0.12	0.02
19	0.03	0.05	-0.04	-0.17	0.01	-0.07	-0.17	0.01
21	0.12	0.05	-0.02	-0.17	0.07	-0.04	0.02	-0.01
22	0.10	0.21	-0.08	-0.21	-0.03	-0.16	-0.09	-0.14
23	0.37	-0.01	0.22	-0.22	-0.19	-0.02	0.07	-0.10
24	0.22	-0.07	-0.13	0.12	0.21	-0.05	0.12	0.01
25	0.17	-0.10	0.22	0.05	0.19	-0.01	0.05	0.11
26	-0.25	0.21	0.27	0.00	-0.11	-0.06	0.09	0.21
27	1.00	-0.29	-0.09	0.07	0.00	0.15	-0.02	0.00
28	-0.29	1.00	0.11	-0.02	-0.07	-0.05	-0.02	0.01
29	-0.09	0.11	1.00	-0.10	-0.06	0.01	0.19	0.11
30	0.07	-0.02	-0.10	1.00	0.11	0.00	0.28	0.11
31	0.00	-0.07	-0.06	0.11	1.00	-0.11	-0.07	0.00
32	0.15	-0.05	0.01	0.00	-0.11	1.00	-0.18	-0.11
33	-0.02	-0.02	0.19	0.28	-0.07	-0.18	1.00	0.47
34	0.00	0.01	0.11	0.11	0.00	-0.11	0.47	1.00
35	0.05	0.10	-0.07	-0.12	0.15	0.11	0.07	-0.01
36	0.04	0.05	-0.02	0.12	0.07	-0.04	-0.17	-0.10
37	-0.04	0.05	0.16	-0.07	-0.26	0.05	0.02	0.15
38	0.29	0.10	-0.07	-0.02	0.39	0.11	-0.21	-0.17
39	0.35	-0.12	-0.17	0.04	-0.12	0.16	-0.13	-0.04
40	-0.04	-0.14	-0.07	-0.02	0.18	0.21	-0.31	-0.15
41	0.00	0.01	0.03	0.02	0.00	-0.03	0.20	0.08
42	0.29	-0.35	-0.12	-0.07	-0.01	0.17	-0.25	-0.01
43	-0.13	0.15	0.07	-0.07	-0.39	-0.11	0.02	-0.23
44	0.16	-0.04	0.07	-0.35	-0.24	-0.05	-0.05	-0.15
45	-0.04	-0.21	-0.02	-0.07	0.07	0.13	-0.07	0.07
46	-0.27	0.45	0.33	-0.22	-0.04	0.00	-0.13	-0.04
47	-0.12	-0.01	0.13	-0.11	-0.16	-0.22	0.00	-0.07
48	0.36	-0.23	0.12	0.00	0.35	0.06	-0.36	-0.42

Tower of London Problems

	35	36	37	38	39	40	41	42
2	0.01	-0.18	0.16	-0.10	0.11	-0.04	0.02	0.08
3	-0.12	0.04	0.20	0.12	0.08	-0.12	-0.04	-0.04
4	-0.11	-0.13	0.04	0.14	0.24	0.13	-0.05	-0.09
5	0.04	0.18	0.01	0.04	0.24	0.33	-0.13	0.14
6	0.17	0.10	0.10	0.09	-0.04	-0.10	0.00	-0.07
7	0.17	-0.02	0.15	0.34	-0.12	0.02	0.15	-0.14
8	0.20	-0.16	0.01	0.12	0.24	0.08	0.03	0.06
9	-0.02	0.00	0.00	-0.02	0.24	0.00	0.13	0.19
10	0.29	0.05	-0.09	0.29	0.20	-0.05	0.08	0.00
11	0.21	-0.12	-0.02	0.21	0.31	0.12	-0.02	0.16
12	-0.14	0.11	0.22	-0.03	0.05	-0.22	0.07	0.14
13	0.29	-0.27	0.09	-0.07	-0.06	-0.21	0.18	-0.09
14	-0.25	-0.02	0.17	-0.07	-0.04	-0.17	-0.02	-0.11
15	0.05	-0.15	-0.15	0.29	0.06	0.03	0.18	0.02
16	0.10	-0.06	0.04	0.10	0.24	-0.14	0.26	0.05
17	0.10	0.04	0.24	-0.10	-0.14	0.16	0.07	-0.23
18	0.01	-0.07	-0.07	0.01	-0.11	-0.27	0.23	-0.03
19	0.08	-0.20	0.26	0.08	0.00	-0.26	0.01	0.06
21	0.32	0.04	0.13	0.24	-0.12	-0.13	-0.18	0.01
22	0.29	0.01	-0.10	0.08	0.05	-0.11	0.07	0.14
23	-0.04	-0.08	0.01	0.05	0.38	0.08	-0.10	0.08
24	0.26	-0.14	0.07	0.26	0.20	0.14	0.01	0.04
25	-0.05	0.01	-0.08	0.04	-0.08	0.16	-0.13	0.06
26	-0.06	0.05	-0.04	0.03	0.00	-0.13	0.13	0.01
27	0.05	0.04	-0.04	0.29	0.35	-0.04	0.00	0.29
28	0.10	0.05	0.05	0.10	-0.12	-0.14	0.01	-0.35
29	-0.07	-0.02	0.16	-0.07	-0.17	-0.07	0.03	-0.12
30	-0.12	0.12	-0.07	-0.02	0.04	-0.02	0.02	-0.07
31	0.15	0.07	-0.26	0.39	-0.12	0.18	0.00	-0.01
32	0.11	-0.04	0.05	0.11	0.16	0.21	-0.03	0.17
33	0.07	-0.17	0.02	-0.21	-0.13	-0.31	0.20	-0.25
34	-0.01	-0.10	0.15	-0.17	-0.04	-0.15	0.08	-0.01
35	1.00	0.07	-0.02	0.34	0.04	0.10	-0.01	-0.14
36	0.07	1.00	-0.14	0.15	-0.04	0.22	-0.18	0.09
37	-0.02	-0.14	1.00	-0.02	-0.04	-0.30	-0.01	-0.24
38	0.34	0.15	-0.02	1.00	0.20	0.10	-0.17	0.19
39	0.04	-0.04	-0.04	0.20	1.00	0.12	0.04	0.27
40	0.10	0.22	-0.30	0.10	0.12	1.00	-0.23	0.24
41	-0.01	-0.18	-0.01	-0.17	0.04	-0.23	1.00	0.07
42	-0.14	0.09	-0.24	0.19	0.27	0.24	0.07	1.00
43	0.08	-0.07	-0.07	-0.25	0.12	-0.10	0.17	0.05
44	0.08	0.04	-0.05	-0.01	0.17	-0.04	-0.06	0.03
45	-0.02	-0.14	0.21	0.07	0.12	-0.04	0.07	0.43
46	0.04	0.12	0.12	-0.12	-0.15	-0.12	0.04	-0.27
47	-0.13	0.10	-0.09	-0.32	0.09	-0.01	0.02	-0.08
48	0.14	-0.01	0.07	0.54	0.15	0.01	-0.11	0.13

Tower of London Problems

	43	44	tol45	tol46	tol47	tol48
2	0.10	-0.14	0.16	0.11	0.15	0.07
3	-0.04	0.00	0.12	0.08	0.09	0.08
4	0.03	-0.12	0.12	0.32	0.22	0.02
5	0.13	0.20	0.27	0.16	0.27	0.02
6	-0.17	-0.20	0.18	0.12	-0.02	0.04
7	-0.09	0.08	-0.10	0.28	-0.13	0.30
8	0.13	0.01	0.01	0.08	0.27	0.19
9	0.15	0.32	0.26	0.12	0.23	0.21
10	-0.02	0.24	-0.09	-0.20	-0.18	0.17
11	-0.12	0.05	0.17	-0.22	-0.21	0.18
12	-0.08	-0.05	0.11	-0.05	0.23	-0.09
13	0.30	0.14	0.09	0.17	0.19	0.14
14	0.16	-0.05	0.07	0.04	0.32	0.09
15	0.18	0.27	0.09	-0.28	-0.08	0.14
16	0.20	0.22	0.24	0.05	0.16	0.29
17	0.00	-0.10	-0.16	0.42	0.16	-0.18
18	0.21	0.10	0.04	0.11	0.27	0.29
19	0.07	0.15	0.11	0.00	0.18	0.27
21	-0.15	-0.15	0.04	0.04	0.10	0.15
22	0.24	0.07	0.11	0.05	0.11	0.12
23	0.04	0.47	0.10	-0.04	0.15	0.08
24	-0.06	0.10	0.07	-0.20	-0.11	0.19
25	-0.12	0.01	-0.16	0.00	-0.01	0.11
26	0.22	0.03	0.13	0.32	-0.04	-0.18
27	-0.13	0.16	-0.04	-0.27	-0.12	0.36
28	0.15	-0.04	-0.21	0.45	-0.01	-0.23
29	0.07	0.07	-0.02	0.33	0.13	0.12
30	-0.07	-0.35	-0.07	-0.22	-0.11	0.00
31	-0.39	-0.24	0.07	-0.04	-0.16	0.35
32	-0.11	-0.05	0.13	0.00	-0.22	0.06
33	0.02	-0.05	-0.07	-0.13	0.00	-0.36
34	-0.23	-0.15	0.07	-0.04	-0.07	-0.42
35	0.08	0.08	-0.02	0.04	-0.13	0.14
36	-0.07	0.04	-0.14	0.12	0.10	-0.01
37	-0.07	-0.05	0.21	0.12	-0.09	0.07
38	-0.25	-0.01	0.07	-0.12	-0.32	0.54
39	0.12	0.17	0.12	-0.15	0.09	0.15
40	-0.10	-0.04	-0.04	-0.12	-0.01	0.01
41	0.17	-0.06	0.07	0.04	0.02	-0.11
42	0.05	0.03	0.43	-0.27	-0.08	0.13
43	1.00	0.28	-0.07	0.04	0.23	-0.06
44	0.28	1.00	0.04	-0.09	0.08	0.13
45	-0.07	0.04	1.00	-0.12	-0.09	0.07
46	0.04	-0.09	-0.12	1.00	0.18	-0.08
47	0.23	0.08	-0.09	0.18	1.00	0.05
48	-0.06	0.13	0.07	-0.08	0.05	1.00