The Effects of Frontal Lobe Lesions on Goal Achievement in the Water Jug Task

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Abstract

Patients with prefrontal cortex lesions are impaired on a variety of planning and problem-solving tasks. We examined the problem-solving performance of 27 patients with focal frontal lobe damage on the Water Jug task. The Water Jug task has never been used to assess problem-solving ability in neurologically impaired patients nor in functional neuro-imaging studies, despite sharing structural similarities with other tasks sensitive to prefrontal cortex function, including the Tower of Hanoi, Tower of London, and Wisconsin Card Sorting Task (WCST). Our results demonstrate that the Water Jug task invokes a unique combination of problem-solving and planning strategies, allowing a more precise identification of frontal lobe lesion patients’ cognitive deficits. All participants (patients and matched controls) appear to be utilizing a hill-climbing strategy that does not require sophisticated planning; however, frontal lobe lesion patients (FLLs) struggled to make required “counterintuitive moves” not predicted by this strategy and found within both solution paths. Left and bilateral FLLs were more impaired than right FLLs. Analysis of the left hemisphere brain regions encompassed by the lesions of these patients found that poor performance was linked to left dorsolateral prefrontal cortex damage. We propose that patients with left dorsolateral prefrontal cortex lesions have difficulty making a decision requiring the conceptual comparison of nonverbal stimuli, manipulation of select representations of potential solutions, and are unable to appropriately inhibit a response in keeping with the final goal.

INTRODUCTION

Historically, the role of the prefrontal cortex in complex cognition has been assessed using a small number of problem-solving tasks, including the Tower of London (Carlin et al., 2000; Morris, Ahmed, Syed, & Toone, 1993; Shallice, 1982), Tower of Hanoi (Morris, Miotto, Feigenbaum, Bullock, & Polkey, 1997; Goel & Grafman, 1995), and Wisconsin Card Sorting Task (WCST) (Milner, 1963, 1964). Studies of frontal lobe lesion patients’ (FLL) performance have demonstrated that each of these tasks emphasizes particular higher-level cognitive functions dependent upon intact frontal lobe function and necessary for successful problem-solving. The Tower of London is routinely used to assess some aspects of planning (Carlin et al., 2000; Shallice, 1982). The Tower of Hanoi requires inhibition of a response in keeping with the final goal, but not the immediate state (Goel & Grafman, 1995). The WCST is believed to highlight working memory function and concept formation/shift- ing (Dunbar & Sussmann, 1995). However, this list of dissociations between the cognitive demands of these tasks may prove to be too simplistic. Solving each of these tasks involves multiple and overlapping higher-level cognitive functions. Some secondary cognitive functions may be equally as important in general problem-solving ability, but may only emerge with different task demands.

In the present study, we administered the Water Jug task (initially described by Luchins, 1942) to FLLs. The cognitive processing demands of the Water Jug task can be viewed as a unique combination of those entailed by the Tower of Hanoi and Tower of London. Goel and Grafman (1995) have proposed that unlike the Tower of Hanoi, the Tower of London does not require (1) recursion, (2) the maintenance of a subgoal stack, and (3) a counterintuitive move. The Water Jug task is similar to the Tower of London on the first two points, and is similar to the Tower of Hanoi because it does require a counterintuitive move. The Water Jug task differs from the Tower of London task because it does not require planning (Carlin et al., 2000; Shallice, 1982; Atwood and Polson, 1980). Formal cognitive processing analyses have suggested that successfully solving the Water Jug task requires a unique problem-solving strategy. By investigating the performance of FLLs on this task, we hoped to increase our understanding of the cognitive processes dependent upon frontal lobe function that are involved in problem-solving.

The Water Jug task is structurally similar to the Tower of Hanoi and the Tower of London tasks. Like these tower tasks, the Water Jug task requires the solver to move from an initial state to a goal state. Both tower tasks

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require the manipulation of rings within a three-peg state space according to a set of rules. Similarly, the Water Jug task involves the manipulation of defined material (i.e., discrete quantities of water) within a state space defined by three regions (i.e., jars) according to a set of predetermined rules. In the task version used in this experiment, there were three jars of different capacities: Jar A = 8 units of water, Jar B = 5 units of water, and Jar C = 3 units of water. At the initial state (Jar A = 8 units and Jars B and C = 0 units), participants were told to begin pouring water between the jars until reaching the goal state (Jars A and B = 4 units, Jar C = 0 units).

Despite the Water Jug task’s similarities to the commonly used tower problems, we know of no prior studies examining the relationship between solving the Water Jug task and human prefrontal cortex function. However, formal cognitive processing models of the Water Jug task and comparisons to the tower tasks have been discussed within both problem-solving and artificial intelligence literatures (Atwood & Polson, 1976; Atwood, Masson, & Polson, 1980; Ernst & Newell, 1969). Ernst and Newell (1969) classified both the Water Jug and Tower of Hanoi tasks as MOVE problems based on each task’s use of complex operators to generate successor states from a current state. Ernst and Newell then created an artificial intelligence model, the general problem solver (GPS), to apply means-ends heuristics in solving a variety of MOVE problems. GPS’s problem-solving heuristics established subgoals at each successive state by detecting differences between the goal state and a potential future state (Ernst & Newell, 1969). While GPS successfully solved the Tower of Hanoi, the model failed to solve the Water Jug task. Ernst and Newell hypothesized that the GPS would have successfully solved the Water Jug task if it had been capable of more effective forward planning (Ernst & Newell, 1969).

In contrast, Atwood and Polson (1976) suggest that GPS’s failure to solve the Water Jug task was due to its rigid dependence upon a subgoal strategy rather than lack of planning ability. Atwood and Polson postulate that no efficacious subgoals can be established if a subgoal method is applied with the Water Jug task. Atwood and Polson also disagreed with Ernst and Newell’s proposal to increase GPS’s forward planning abilities in order to solve the Water Jug task, saying that this would not be representative of human problem-solving, which is restricted by memory limitations (Atwood & Polson, 1976).

Motivated by GPS’s inability to solve the Water Jug task, Atwood and Polson (1976) developed a separate process model to more accurately describe the human cognitive processes involved in solving the task. Like Ernst and Newell’s (1969) GPS model, Atwood and Polson’s model applies means-ends move selection heuristics. However, the fundamental assumption of this model is that participants make all moves using information from the current state and its immediate successors. Atwood and Polson (1980) state that participants are under severe short-term memory restrictions, which makes “planning,” or sequencing a series of future moves from a current state, an ineffective strategy. Rather, solving the Water Jug task depends upon the interaction of means-ends processes and memory processes. Means-ends processing uses a mathematical formula to evaluate the current state as well as all of the possible states that could result from a single move away from the current state. The formula is based upon the assumption that the participant assesses how close each jar would be to the goal state if a particular move is made and that the participant will choose the move in which all jars are closest to the goal state. Using this evaluation function, each state can be assigned a value that can be compared to the evaluation function values (efv) of the possible states. This information is stored in short-term memory. Information regarding previous states is stored in long-term memory and can be retrieved during the evaluation process (Atwood & Polson, 1976).

We propose that the means-ends processing entailed by Atwood and Polson’s (1976) process model describes a hill-climbing strategy. This strategy is based on problem-solvers’ preference to only look one move ahead and make moves that will immediately take them closer to the goal state. Hill-climbing is less demanding than strict means-end analysis because it does not require establishing and maintaining subgoals to lessen the degree of dissimilarity between the current and final states (Lovett & Anderson, 1996).

Based on Atwood & Polson’s (1976) process model, assumptions made by Ernst and Newell’s (1969) GPS model, and our previous findings from patient studies of problem-solving (Carlin et al., 2000; Goel & Graftman, 1995; Graftman, 1995), we predict the following reasons why FLLs could have difficulty solving the Water Jug task. Atwood and Polson (1980) have shown that normal controls (NCs) do not plan ahead while solving this task. It is unlikely that any impairment in problem-solving ability could be primarily accounted for by a planning deficit, such as that seen in FLLs’ performance on the Tower of London task (Carlin et al., 2000; Shallice, 1982). A more plausible locus of FLLs’ potential difficulty can be described as a failure to adjust their problem-solving strategy to make moves that are not predicted by the basic means-ends heuristics underlying the hill-climbing strategy. Within both solution paths of the task, there are certain moves, which we call “counterintuitive moves,” that require participants to select a move resulting in a state that is less like the goal state than the previous state. Therefore, making these moves entails a violation of the hill-climbing strategy. If FLLs’ performance at these particular states differs from the performance of NCs, then frontal lobe processes may be required to inhibit the optimal move predicted by hill-climbing or means-ends heuristics in order to make the
"counterintuitive move" required to reach the goal state. As a result, FLLs will make more moves back to previous states rather than towards the goal state. This is arguably similar to the goal-subgoal resolution necessary to solve the Tower of Hanoi task that is difficult for FLLs to perform (Goel & Grafman, 1995).

Atwood and Polson’s (1976) Water Jug process model implies a clear role for working memory (referred to as short-term memory) to temporarily store information during the generation and evaluation of possible moves from the current state (Figure 1). While FLLs can encode and store new information, and retrieve old information, they can have difficulties retaining or applying temporary information towards a current goal (Fuster, 1989). Goel and Grafman (1995) suggest that memory deficits (an inability to activate and retain information about current and future states) may contribute to FLLs’ impairments in solving the Tower of Hanoi task. In addition, Dunbar and Sussman (1995) have argued that FLLs’ inability to shift attention or strategies when task demands change can be accounted for by their working memory deficits (Dunbar & Sussman, 1995). These memory deficits could prohibit FLLs from retaining representations of the current and future states as well as prevent them from recalling previous states and moves. This additional impairment could further hinder FLLs’ ability to modify and make exceptions to their problem-solving strategy when faced with counterintuitive moves.

This study has three goals. The first is to determine whether cognitive processes mediated by the prefrontal cortex are necessary for solving the Water Jug task, and if so, add to the body of literature supporting the importance of frontal lobe function in human problem-solving. The second goal of this study is to evaluate the models of the Water Jug task, focusing on the interaction between memory processes and hill-climbing or means-end heuristics involved in move selection processes as proposed by Atwood and Polson (1976), and correlating these processes to observed human performance. Finally, the cognitive processes involved in the Water Jug task will be compared to those involved in the Tower of Hanoi, to characterize any relationship between the two tasks.

RESULTS
Demographics
The FLLs and normal controls (NCs) did not differ significantly in either age [\(U = 329, p > .5\), two-tailed] or education [\(U = 318.5, p > .4\), two-tailed].

Figure 1. Flow chart of the possible states and moves for both the L and R solution paths in the (8, 5, 3) Water Jug task. For each state, the three numbers in parentheses represent the amount of water in Jars A, B, and C, respectively. The italicized number outside of the parentheses is the cf of that current state. (From “Further Explorations with a Process Model for Water Jug Problems,” by M. E. Atwood, M. E. J. Masson, and P. G. Polson, 1980, Memory and Cognition, 8, p. 183. Copyright 1980 by the Psychonomic Society, Inc. Adapted with permission).
Number of Solvers and Solution Path Choices

Only 52% of FLLs reached the goal state, while 89% of NCs reached the goal state \(\chi^2(1, n = 54) = 8.88, p < .003\). Of participants who solved the task, there was a significant difference between the pathways chosen by FLLs and NCs (Fisher’s Exact Test \(\chi^2(1, n = 54) = 4.78, p < .04\)). 83% of NC solvers followed the R solution path (17% used the L solution path), while only 50% of FLL solvers used the R solution path (50% used the L solution path). There were no significant differences between left (LFL), right (RFL), or bilateral (BFL) patients’ pathway choices \(\chi^2(4, n = 27) = 3.49, p > .45\) or these groups’ ability to reach the goal state \(\chi^2(2, n = 27) = 1.93, p > .35\).

Counterintuitive Move Analysis

The performance of FLLs significantly differed from that of NCs \(F(5,45) = 3.11, p < .02\). FLLs \((M = 7.90)\) made more backward reversible moves than NCs \((M = 3.69)\) \(F(1,49) = 4.16, p < .05\), FLLs \((M = 0.01)\) made more looping moves than NCs \((M = 7.39)\) \(F(1,49) = 11.32, p < .002\), FLLs \((M = 3.88)\) made more returns to the start state than NCs \((M = 0.67)\) \(F(1,49) = 5.60, p < .05\), and FLLs \((M = 14.13)\) made more solution path changes than NCs \((M = 7.83)\) \(F(1,49) = 7.74, p < .01\). There was a nonsignificant trend for FLLs \((M = 34.21)\) to make fewer counterintuitive moves than NCs \((M = 38.96)\) \(F(1,49) = 3.12, p = .084\). These findings suggest that FLLs have a tendency to return to an earlier state rather than make a counterintuitive move. To examine this hypothesis, we compared FLLs’ and NCs’ choices of moves relative to their total number of moves made at each state in the pathway where a counterintuitive move is required to proceed directly to the goal state.

L Solution Path

There are three counterintuitive moves in the L solution path: AB, BC, and CD. At State A \((efv = 2)\), move AB is a counterintuitive move. There were no significant differences between FLLs’ and NCs’ move selections at this state \(F(4,27) = 2.32, p > .08\).

The second counterintuitive move in the L solution path is required to advance from State B \((efv = 3)\) to State C \((efv = 3)\). There were no differences between FLLs’ and NCs’ move selections at this state \(F(4,24) = 1.49, p > .20\).

The final counterintuitive move in the L solution path is from State C \((efv = 3)\) to State D \((efv = 7)\). FLLs’ and NCs’ performance at this state was significantly different \(F(3,21) = 3.87, p < .025\). FLLs \((M = 30.42)\) made more backward reversible moves than NCs \((M = 4.17)\) \(F(1,23) = 4.73, p < .05\). NCs \((M = 63.89)\) were more likely to make a looping move to State R \((efv = 2)\) than FLLs \((M = 18.96)\) \(F(1,23) = 11.46, p < .005\). It should be noted that this looping move is the most acceptable alternative to the counterintuitive move.

R Solution Path

There are three counterintuitive moves in the R solution path: RU, UV, and VW. As seen in the L solution path, FLLs demonstrated haphazard movement through the R solution path upon reaching states requiring counterintuitive moves to proceed directly to the goal state (see Figure 2).

At State R \((efv = 2)\), a counterintuitive move is required to advance to State U \((efv = 3)\). There were no differences between FLLs’ and NCs’ move selection \(F(3,44) = 1.11, p > .35\).

At State U \((efv = 3)\), a counterintuitive move is required to proceed to State V \((efv = 4)\). FLLs’ and NCs’ performance at this state significantly differed \(F(4, 40) = 2.62, p < .05\). FLLs \((M = 56.78)\) were less likely to make the critical counterintuitive moves than NCs \((M = 81.44)\) \(F(1,43) = 8.40, p < .01\) and FLLs \((M = 27.45)\) made more looping moves to State I than NCs \((M = 10.28)\) \(F(1,43) = 6.81, p < .02\).

Upon reaching State V \((efv = 4)\), participants must make a final counterintuitive move to State W \((efv = 6)\). There were no significant differences between FLLs’ and NCs’ move selections at this state \(F(3,38) = 1.94, p > .15\).

Role of Left Prefrontal Cortex

When FLLs were divided by lesion laterality and compared to NCs, the performances of the four groups were significantly different \(F(15,125) = 2.37, p < .01\). In general, FLLs with left prefrontal cortex damage (LFLLs and BFLLs) were more impaired on the Water Jug task than unilateral RFLLs. LFLLs \((M = 11.40)\) and BFLLs \((M = 9.44)\) had higher ratios of backward reversible moves compared to NCs \((M = 3.69)\) and RFLLs \((M = 3.29)\) \(F(3,47) = 3.35, p < .03\). LFLLs \((M = 8.00)\) and BFLLs \((M = 4.04)\) had higher ratios of returns to the start state than RFLLs \((M = 0.47)\) and NCs \((M = 0.67)\) \(F(3,47) = 5.56, p < .005\). The difference between LFLLs’ \((M = 13.73)\), BFLLs’ \((M = 18.07)\), and RFLLs’ \((M = 12.26)\) ratios of looping moves was considerably less pronounced but the overall difference between these groups and NCs \((M = 7.39)\) was significant \(F(3,47) = 4.77, p < .01\). The differences between the groups’ ratios of solution path changes \(F(3,47) = 2.79, p = .051\) and counterintuitive moves \(F(3,47) = 2.62, p = .062\) just failed to reach significance. However, RFLLs \((M = 38.85)\) had similar ratios of counterintuitive moves to NCs \((M = 38.96)\) while LFLLs \((M = 31.00)\) and BFLLs \((M = 32.46)\) made fewer counterintuitive moves.

Damage to left dorsolateral prefrontal cortex (Brodmann’s areas \([BA]\) 8, 9, 10, 44, 45, and 46) positively correlated with impaired performance on the Water Jug task.

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Patients with unilateral left hemisphere damage to this region \((n = 8)\) had lower ratios of counterintuitive moves and greater ratios of backward reversible moves, returns to the start state, and solution path changes compared to patients with right unilateral damage to this region \((n = 9)\) (see Table 1).

Damage to the left cingulate cortex (BA 24) also correlated with poorer Water Jug performance, although to a lesser degree than damage to the left dorsolateral prefrontal cortex. FLLs with unilateral left cingulate cortex damage \((n = 5)\) had higher ratios of returns to the start state and solution path changes than FLLs with right unilateral lesions to this area \((n = 10)\) (see Table 1).

There were no significant differences between patients with left unilateral ventromedial cortex damage and patients with right unilateral ventromedial cortex damage; however, the numbers of patients with unilateral left or right damage to this region were small \((n = 5\) and 2, respectively).

**Significant Covariate Factors**

Three covariate factors (age, education, and sex) were included in the group analyses. When comparing FLLs to NCs, there was a significant multivariate effect of age \([F(5,45) = 2.44, p = .048]\). Older participants had...
greater ratios of backward reversible moves \( F(1,49) = 8.99, p < .005 \) and returns to the start state \( F(1,49) = 4.34, p < .05 \). There was also a significant multivariate effect of education \( F(5,45) = 2.57, p = .04 \). Participants with more education made fewer ratios of backward reversible moves \( F(1,49) = 11.51, p < .002 \) and more counterintuitive moves \( F(1,49) = 5.78, p < .03 \). There were no significant multivariate effects of any of the covariate factors for the lesion laterality (RFLL, LFLL, BFLL, and NC) analysis.

**Correlations to Total Brain Volume Loss**

There were no significant correlations between volume loss and Water Jug measures of performance.

**Correlations to Scores on Measures of General Intelligence**

There were no significant correlations between Water Jug performance and measures of general intelligence.

**Correlations to General Memory Function**

**WMS-R**

There were no significant correlations between FLLs’ memory index scores and Water Jug performance.

**WMS-III**

FLLs’ auditory immediate and immediate memory index scores negatively correlated with returns to start state \( r = -0.92, p < .002 \) and \( r = -0.91, p < .002 \), respectively.

**Correlations to Tower of Hanoi Performance**

Sixteen of the 27 FLLs (4 LFLL, 5 RFLL, and 7 BFLL) were also tested on the Tower of Hanoi task (see Goel & Grafman, 1995). These patients’ mean Tower of Hanoi scores were correlated with the sensitive measures of Water Jug performance. A higher Tower of Hanoi score represents a better performance. There were no significant correlations between any measure of Water Jug performance and Tower of Hanoi score.

**DISCUSSION**

FLLs are impaired on the Water Jug task. Volume loss, memory index scores, and intelligence index scores could not account for impaired performance across all measures. Not surprisingly, participants with higher education levels made more counterintuitive moves and fewer backward reversible moves and older participants made more backward reversible moves and returns to start state. Compared to NCs, fewer FLLs reached the goal state. FLLs made more moves away from the goal state (backward reversible moves, looping moves, and returns to start state) than NCs. FLLs also made relatively fewer counterintuitive moves than NCs in both solution pathways. Upon reaching a state requiring a counterintuitive move to proceed directly towards the goal state, FLLs made fewer counterintuitive moves and more backward reversible and looping moves towards the start state.

In general, LFLLs and BFLLs were significantly more impaired than RFLLs. RFLLs and NCs had similar proportions of moves away from the goal state (backward reversible moves, looping moves, and returns to start state). While RFLLs did not perform similarly to NCs on all measures, these critical findings imply that the cognitive processes required for solving the Water Jug task are largely dependent upon intact left frontal lobe function. We will discuss performance differences between patients with unilateral left hemisphere lesions and unilateral right hemisphere lesions in more detail below.

These findings indicate that the means-ends processing heuristics outlined by Atwood and Polson (1976) are sensitive to discerning problem-solving differences between FLLs’ and NCs’ Water Jug performance and demonstrate that the key cognitive processes involved in solving the Water Jug task are dependent upon intact prefrontal cortex functioning.

**Water Jug Task Solving Strategy**

To build a cohesive description of actual human problem-solving strategies in the Water Jug task, we reviewed common problem-solving heuristics. While heuristics do not guarantee correct solutions, they make solving problems tractable, and can be applied to novel situations involved in any type of problem-solving and concept attainment task. As such, these heuristics constitute very general methods of arriving at a solution that can be used in virtually any situation.
The means-ends analysis heuristic requires that the problem-solver first set a goal of reaching the final state of a problem. If this goal cannot be directly achieved, then the problem-solver must set another goal (a subgoal) of removing any barriers prohibiting final goal achievement. In many problems, such as the Tower of Hanoi, the problem-solver will have to set up a variety of subgoals before reaching the final goal state. Simon (1975) has described this strategy for solving the Tower of Hanoi as a goal-recursion strategy. However, Simon also identified three other potential problem-solving strategies for solving the Tower of Hanoi task: (1) perceptual strategy, (2) sophisticated perceptual strategy, and (3) move-pattern strategy. Each of these strategies place different demands on memory and emphasize distinct elements of the problem (Simon, 1975). Goel and Graffman (1995) have argued that all participants (including both NCs and FLs) use a perceptual strategy, rather than a strict means-ends heuristic to solve the Tower of Hanoi task. Simon posits that this unsophisticated strategy greatly reduces short-term memory demands by merely requiring the perception of the current problem state's features to make the next move. The maintenance of a goal state representation during the execution of the process is not necessary (Simon, 1975).

Simon’s (1975) perceptual strategy for solving the Tower of Hanoi can also be regarded as a hill-climbing strategy (described earlier) and we will refer to it as such for the remainder of this discussion. The reader will recall that the hill-climbing strategy only requires the problem-solver to look one move ahead, to evaluate all possible moves and pick a move that brings him or her immediately closer to the goal state. The problem-solver does not have to remember all of the subgoals in the task. While hill-climbing heuristics are simpler than formal means-ends analysis, a more general heuristic underlies both strategies. The generate-and-test heuristic requires that the problem-solver generate all possible moves and evaluate which move will allow him or her to achieve the goal or subgoal. Goel and Graffman’s (1995) previous findings demonstrate that FLs’ impaired Tower of Hanoi performance cannot be fully characterized as either a failure to generate possible moves or as a deficit in the evaluation of those possible moves. Rather, successfully solving the Tower of Hanoi requires that participants violate their hill-climbing strategy at certain points in the problem by making moves that appear to take them away from the goal state. FLs are unable to inhibit a response that is in keeping with the final goal, but not the immediate state (Goel & Graffman, 1995) and therefore, will not violate the hill-climbing strategy.

Like the perceptual strategy for solving the Tower of Hanoi problem, the Water Jug problem-solving strategy predicted by Atwood and Polson (1976) can also be regarded as a hill-climbing heuristic (Lovett & Anderson, 1996). At each state, a participant must perceive the features of that state (i.e., how many ounces are in each jar) and generate representations of the possible future states. To select a move, the problem-solver compares the features of a potential future state to the features of the goal state, while recalling the features of past states. Atwood and Polson’s evaluation function \[ e_i = (C_i(A) - G(A)) + (C_i(B) - G(B)) \] returns a value quantifying the degree of perceptual difference between any potential state and the goal state. The value of \( e_i \) becomes smaller (closer to 0) if the capacities of Jars A and B are closer to 4 oz (closer to the goal state). Atwood and Polson define an “optimal” move as the possible move that leads to the biggest drop in \( e_i \) between the current state and the future state. Any move that results in a lower value of \( e_i \) is considered “acceptable” (Atwood & Polson, 1976). By this heuristic, problem-solvers should select moves that yield a future state that appears closest to the goal state (i.e., has 4 oz of water in Jar A and 4 oz of water in Jar B). However, this hill-climbing strategy will fail to solve the Water Jug problem if it is universally applied. Water Jug problem solvers must make certain counterintuitive moves that result in states more closely resembling the start state than the goal state.

The reader will recall that three counterintuitive moves are found in each of the two Water Jug solution paths. While FLs and NCs were not significantly different in their overall likelihood to select a counterintuitive move \( (M = 38.96) \) \[ F(1,49) = 3.12, p = .084 \], there were significant differences in their move selection at State C in the L solution path and State U in the R solution path. When FLs reached either of these states requiring a counterintuitive move to proceed directly to the goal state, they were more likely to make a looping or backward reversible move returning them closer to the start state than NCs. This suggests that FLs will choose to return to a previous state if the forward move towards the goal requires a violation of their hill-climbing strategy. In contrast, NCs make more counterintuitive moves because they can adjust their problem-solving strategy at these points, despite their history of success in applying the hill-climbing heuristic (Lovett & Anderson, 1996).

Application of the hill-climbing strategy can account for the differences between FLs’ and NCs’ performance at States C and U, as well as NCs’ preference for solution path R over solution path L. In solution path L, the counterintuitive move from State C to State D requires the solver to go from a state with 2 oz of water in Jar A (State C) to 7 oz of water in Jar A (State D), a state that closely resembles the start state. In solution path R, two counterintuitive moves result in states with 6 oz of water in Jar A. Six ounces is equidistant between eight (start state) and four (goal state), therefore, it is unclear whether this state more closely resembles the initial state or the goal state. Following solution path R does not appear to take the solver as far away from the goal state...
as following solution path L. In addition, the analysis of FLLs' and NCs' move selections at each state requiring a counterintuitive move only found significant differences at States C and U. As stated above, making a counterintuitive move from either of these states results in either a state that closely resembles the start state (State D) or is equally similar to both the start state and the goal state (State V). These are the first counterintuitive moves in each solution path resulting in states that do not perceptually resemble the goal state. FLLs are more likely to make a disadvantageous move (looping or backward reversible) when they encounter these critical counterintuitive moves. This suggests that FLLs struggle to make an initial violation of the hill-climbing strategy, resulting in perseverative, backward reversible and looping move selections. Once FLLs have learned to make this initial violation, their performance at other states requiring a counterintuitive move is no different from NCs.

**Comparison to Other Tasks and the Role of the Left Prefrontal Cortex**

Given that both the Water Jug and Tower of Hanoi tasks elicit a hill-climbing strategy, we were somewhat surprised that there were no significant correlations between critical measures of Water Jug performance and Tower of Hanoi score. However, only 16 of the 27 patients included in this study were tested on both tasks. Most likely, the lack of significant finding can be attributed to differences between the dependent measures of the two tasks. The dependent measures used to assess Water Jug performance specifically captured either the solver’s ability to violate (counterintuitive moves) or apply (backward reversible, looping, returns to start state, solution path changes) the hill-climbing strategy. The Tower of Hanoi score included both the solver's successful application and violation of the hill-climbing strategy and was a more general measure of total performance.

More powerful evidence of participants’ application of a common strategy to solve both the Tower of Hanoi and Water Jug tasks is our finding that intact left dorsolateral prefrontal cortex function is critical for successful Water Jug performance. Damage to the left dorsolateral prefrontal cortex significantly correlated with impaired performance as measured by decreased ratios of counterintuitive moves and increased ratios of backward reversible moves, returns to the start state, and solution path changes. Left frontal lobe damaged patients are also impaired in solving the Tower of Hanoi (Morris et al., 1997). Morris et al. (1997) characterize this deficit as an inability to inhibit a response in keeping with the final goal. Results from problem-solving studies using the Tower of London are ambiguous with regard to specific left frontal lobe function. Certain behavioral studies of FLLs (Shallice, 1982) and neuroimaging studies of normal participants (Morris et al., 1993) implicate a critical role for the left frontal cortex. Other behavioral studies (Carlin et al., 2000; Owen, Downes, Sahakian, Polkey, & Robbins, 1990; Shallice, 1988) and neuroimaging studies (Dagher, Owen, Boecker, & Brooks, 1999; Baker et al., 1996) find no significant relationship between successful performance and intact left frontal cortex function. In light of this conflicting evidence, it is difficult to discern the differences and similarities between the neural pathways recruited by the Tower of London and Water Jug tasks. Again, this could be a reflection of the Tower of London’s task demands that tempt the solver to plan ahead (Carlin et al., 2000; Shallice, 1982). Participants do not plan ahead while solving the Water Jug task (Atwood and Polson, 1980).

Impaired performance on the WCST is most consistently associated with left dorsolateral prefrontal cortex function (Milner, 1963), although some right FLLs can show equally diminished WCST performance (Milner, 1964; Milner & Petrides, 1984). Drewes (1974) explored this distinction between right FLLs’ and left FLLs’ WCST ability and found differences between the two groups depending on the measure of performance. Specifically, the two groups were equal on measures of perseverative, errors, while left FLLs were impaired on measures of number correct and of category sorting tendencies (Drewes, 1974). These results suggest that unlike the Water Jug task, the WCST appears to be at least somewhat sensitive to right frontal lobe function.

We propose that the different neural pathways elicited by these tasks are reflective of their relative dependence on “working memory,” commonly linked to dorsolateral prefrontal cortex function (Courtney, Ungleydeker, Keil, & Haxby, 1997; D’Esposito et al., 1995; Goldman-Rakic, 1987). Dunbar and Sussman (1995) have attributed FLLs’ impaired WCST performance to decreased working memory function that prohibits the application of new feedback information. There is limited evidence that working memory demands differentially affect left and right frontal lobe function. Bechara, Damasio, Tranel, and Anderson (1998) reported that patients with unilateral right dorsolateral prefrontal cortex damage are impaired on a working memory task, while patients with unilateral left dorsolateral prefrontal cortex damage performed similarly to NCs. In contrast, patients with left frontal cortex damage were impaired on a decision-making task (a gambling task, see Bechara, Damasio, Tranel, & Damasio, 1997), while patients with right frontal cortex damage performed similarly to NCs (Bechara et al., 1998). It should be noted that the decision-making task used in this study is particularly sensitive to ventromedial frontal cortex damage, not dorsolateral prefrontal cortex damage (Bechara et al., 1998; Bechara, Damasio, & Damasio, 2000). Nevertheless, these results illustrate that working memory and decision-making are functionally dissociable and may reflect hemispheric asymmetries. Therefore, it is plausible that right FLLs’
WCST impairment may be due to working memory deficits, while left FLs’ impairment may be due to decision-making problems.

If differential WCST performance between right and left FLs is due to the right frontal lobe’s selective sensitivity to working memory demands in problem-solving, then the relatively normal performance of RFLs on the Water Jug task indicates that working memory involvement is secondary to other cognitive processes. Indeed, there were only two significant correlations between memory index scores (WMS-III auditory immediate and WMS-III immediate) and Water Jug performance measures. Given that these measures were not designed to specifically pinpoint working memory function, it could be that the correlation between Water Jug performance and these scores merely reflects mutual sensitivity to dorsolateral prefrontal cortex function. However, it should also be noted that only five patients received the WMS-III and that none of the patients were unilateral left FLs. There were no correlations between Water Jug performance measures and WMS-R memory index scores.

Whether the different pattern of frontal lobe involvement between the WCST and Water Jug tasks can be wholly accounted for by working memory demands remains to be fully explored. However, it is clear that the WCST and Water Jug tasks are structurally different. Miyake et al. (2000) demonstrated that the WCST is best categorized as a “shifting” task, requiring periodic strategy changes. In contrast, the Tower of Hanoi task was classified as an “inhibitory” task, requiring the ability to preclude a move predicted by the adopted problem-solving strategy. By this definition, the Water Jug task can also be characterized as an “inhibitory” task. Given the similarities between the Tower of Hanoi and Water Jug tasks discussed earlier, Miyake et al.’s findings might also have predicted differences between the cognitive processes involved in performance on the Water Jug and WCST tasks that could lead to the recruitment of different neural systems. Indeed, recent neuroimaging evidence has demonstrated that inhibition can be associated with left dorsolateral prefrontal cortex function (BA 45) independent of working memory (Smith & Jonides, 1998).

Finally, we have argued that all participants adopted a perceptual strategy comparing nonverbal representations of state spaces. Our findings then suggest that the left dorsolateral prefrontal cortex may support executive functions (e.g., inhibition) necessary for problem-solving regardless of the nature of the stimuli. This is in keeping with the findings of Glosser and Goodglass (1990), reporting that aphasic patients with left dorsolateral prefrontal cortex lesions are impaired on a nonverbal test of sustained attention and tasks requiring novel responses to visual patterns relative to aphasics without left dorsolateral prefrontal cortex lesions. In addition, Wharton et al. (2000) report a positron emission tomography study of normal participants finding left frontal activation (BA 44 and 45) during analogical reasoning tasks requiring comparison of nonverbal stimuli (Wharton et al., 2000). This combined evidence suggests that the left prefrontal cortex may be needed for decision-making and problem-solving involving conceptual comparisons between nonverbal stimuli.

Indeed, evidence from language comprehension studies has pointed to different general coding strategies between the left and right hemispheres that would predict hemispheric differences in problem-solving. Bee-man (1998) has proposed that the left hemisphere is more successful than the right hemisphere in solving certain types of problems because it activates, manipulates, and maintains a select few representations throughout cognitive processing. In contrast, the right hemisphere activates and maintains multiple representations or solutions (Beeman & Bowden, 2000), making it difficult to select a single representation on which to focus future processing resources (Beeman, 1998). Consequently, the right hemisphere’s “coarse coding” mechanism is advantageous for certain types of problems created by ambiguous context, including those involving verbal material (Beeman, 1998; Beeman et al., 1994; Fiore & Schooler, 1998). The left hemisphere may be superior in focusing attention to identify a single solution to a logical problem. Solving the Water Jug problem requires focused manipulation of select representations to prohibit returning to previous states and recognizing the need to violate the hill-climbing strategy in order to make required counterintuitive moves. Therefore, solving the Water Jug problem is largely dependent upon intact left hemisphere function, and specifically, left prefrontal cortex function.

**Conclusion**

Our findings expand upon previous research examining the role of the prefrontal cortex in human problem-solving. While the GPS’s failure to solve the Water Jug task and success in solving the Tower of Hanoi task first suggested that the two tasks required different problem-solving strategies (Ernst & Newell, 1969), we have demonstrated that human participants employ hill-climbing heuristics to solve both problems. Atwood and Polson’s (1976) process model successfully describes a hill-climbing strategy used by both FLs and NCs to solve the Water Jug problem. This strategy can also be described as Simon’s (1975) simple perceptual strategy for solving the Tower of Hanoi task. Both strategies detect the magnitude of the differences between potential future states and a goal state in order to determine subsequent moves.

As is required to successfully solve the Tower of Hanoi, participants must make moves that violate the hill-climbing strategy to solve the Water Jug task. Coupled with Goel and Grafman’s (1995) study of FLs’
impaired Tower of Hanoi performance, our findings support the necessity of intact left prefrontal cortex function to inhibit a response that is in keeping with the final goal. Successful Water Jug performance can be specifically associated with intact left dorsolateral prefrontal cortex function. We propose that intact functioning of this region is necessary for decision-making requiring the conceptual comparison of structurally dissimilar nonverbal stimuli, select manipulation of representations of potential solutions, and the inhibition of a response generated by an adopted problem-solving strategy.

METHODS

Participants

Twenty-seven patients with focal lesions to the prefrontal cortex (FRs) participated. Nine patients had unilat-
eral right frontal lesions (RFLL), 7 patients had unilateral left frontal lesions (LFLL), and 11 patients had bilateral frontal lesions (BFLL). The size, location, and etiologies of the prefrontal cortex lesions varied. Twenty-four patients were Vietnam War veterans with penetrating missile wounds; two patients were aneurysm/stroke cases, and one patient was a tumor removal case. The involvement of specific structures and brain volume loss for each patient was determined from CT and MRI scans (see Table 2 and Figure 3).

Patients were matched for age, education, handedness, and sex with 27 normal volunteers (NCs) (see Table 3). Normal volunteers were recruited and compensated following the guidelines of the normal volunteer program at the National Institutes of Health.

The average IQ scores for both the FLLs and NCs were assessed. Twenty-four normal volunteers received the National Adult Reading Test (NART) (Nelson, 1991). Three normal volunteers received the Wechsler Adult Intelligence Scale Version R (WAIS-R) (Wechsler, 1981). Twenty-five patients received the WAIS-R and two patients received the Wechsler Adult Intelligence Scale Version III (WAIS-III) (Wechsler, 1997a). Each patient’s
memory performance was also assessed. Twenty-two patients received the Wechsler Memory Scale Version R (WMS-R) (Wechsler, 1987) and five patients received the Wechsler Memory Scale Version III (WMS-III) (Wechsler, 1997b) (see Table 3).

Water Jug Task

The Water Jug task used in this experiment was a computerized version of the 8, 5, and 3 task described by Atwood and Polson (1976) and Luchins (1942). There is a large jar with a capacity of 8 oz, a medium size jar with a capacity of 5 oz, and a small jar with a capacity of 3 oz. In the initial state, the 8-oz jar is full. The goal of the task is to pour between jars to achieve a state where 4 oz of water are in the large (8 oz) jar, and 4 oz of water are in the medium (5 oz) jar. There are no constraints on pouring between jars; however, pouring continues until the original jug is empty or the target jug is full. Eight ounces of water are always involved in the task.

The computerized version of the Water Jug task used in this experiment was developed by Matthews and Schunn (1990). Visual representations of each of the jars are shown on the screen. The jars are labeled A (8 oz), B (5 oz), and C (3 oz) and the maximum capacities are also shown beneath each respective jar. Dark gray shading and labels above each jar represent

Figure 3. (continued)
the current capacity of each jar (e.g., in the initial state, the capacities are 8, 0, and 0).

**Procedure**

To familiarize participants with the pouring procedure, they were first given a practice task requiring them to dictate a series of pouring moves that would result in 5 oz. of water in the large (8 oz.) jar and 3 oz. of water in the medium (5 oz.) jar. After the participant dictated each move, the examiner executed the move using the mouse. The shading in the jars would then change to reflect the current water level in each jar following a move. During the practice task, the experimenter repeated the instructions when necessary. Participants were required to understand the practice task before moving to the actual task. Participants were then given the actual task [to find a series of moves that would result in 4 oz in the large (8 oz) jar and 4 oz in the medium size (5 oz) jar] and told that they would have a maximum of 30 min to perform the task. Like the practice task, participants relayed moves to the experimenter. If the participant did not solve the task in 30 min, the test was discontinued. Neither the examiners nor the computer provided feedback while participants were solving the task.
**Water Jug Measures of Performance**

The computer program automatically counted the total number of moves, tracked the sequence of moves, and found the evaluation function value \( e(i) \) at each state, following the model of Atwood and Polson (1976) and Atwood et al. (1980). The analysis program then generated a state matrix of all possible moves, which provided a method of summarizing the number of moves from each state to another state. Using this information and following Atwood and Polson’s model and Atwood et al.’s application of the model, we assessed performance using the following four dependent measures of disadvantageous problem-solving strategy. Note that the term “reversible” applies to all moves that allow one to return to the state that preceded the resulting state in a single move.

**Backward Reversible Moves**

Moves made to the state that immediately preceded the current state, except moves made back to the transition state (T) or back to the start state (S) (e.g., B to A).

**Looping Moves**

The two possible irreversible moves to States S, L, R, or T that can be made from each state in a solution path.
These moves are “irreversible” because once the move has been made, one cannot return to the state that immediately preceded the current state (e.g., A to R).

**Returns to the Start State**

Moves made to the start (S) state.

**Solution Path Changes**

Moves to states in the right (R) solution path when the previous state was in the left (L) solution path and vice versa (e.g., A to R, U to L).

The following variable was designed to capture violations of a hill-climbing strategy based on Atwood and Polson’s (1976) distinction between “acceptable” and “unacceptable” moves. For our purposes, acceptable moves are defined as any move leading to a future state with a lower efv than the current state. An unacceptable move is defined as any move leading to a future state with a higher efv than the current state.

**Counterintuitive Moves**

Moves leading to a state that is closer to the goal state (G) than the current state and to a state with the same
or higher efv as the current state (moves AB, BC, CD, RU, UV, and VW).

If all of the variables described above are expressed in terms of raw numbers of moves, then any true differences between NCs and FLRs could be obscured by a significant difference in the mean pathlengths of the two groups. Therefore, for each individual participant, the dependent variables described above were transformed into a ratio of the individual's pathlength (total number of moves). These ratios were used in the final analysis.

Finally, there were two categorical variables:
- Solved. The task was solved if “G” is the final state in the participant’s path (i.e., there were 4 oz of water in Jar A and 4 oz of water in Jar B). This variable has two levels: (1) solved and (2) unsolved.
- Solution. If the participant solved the task, their final solution path was recorded. This variable has two levels: (1) L solution and (2) R solution.

To perform the counterintuitive move analysis, we examined each participant's move selections at each state in the pathway where a counterintuitive move is required by calculating a ratio for each move made at these states relative to the total number of moves at that state (i.e., number of times a particular move is made at a state leading to a counterintuitive move/total number of moves made from that state). If a participant did not reach a state, then the ratio was 0/0 and these ratios...
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Standard deviations of mean scores are shown in parentheses.

*The NART provides estimates of WAIS index scores. PFIQ = predicted full scale IQ; PVIQ = predicted verbal index IQ score; PPIQ = predicted performance index IQ.
were excluded from the final analysis. Note that this method produced unequal numbers of FLLs and NCs when the two groups were compared.

**Statistical Analysis**

**Normality of the Distribution**

To determine whether the distribution of the continuous variables were normal in both the FLL and NC groups, we employed the Shapiro-Wilks Test for Normality for each dependent variable in both populations. Only the dependent variable “ratio of counterintuitive moves” was normally distributed. The following variables were not normally distributed: backward reversible moves, looping moves, returns to start state, and changes in solution path.

**Differences Between Groups**

Despite differences in the distributions of the five dependent measures of Water Jug performance, we employed multivariate tests to protect against the increased likelihood of Type I error due to repeated univariate tests. MANCOVAs have been shown to be particularly robust even when violations of normality occur (Stevens, 1996). To assess the differences between the FLL and NC groups, a MANCOVA with the following design was employed: one between-subjects factor of group (two levels: FLL and NC), three covariate factors (age, education, and sex), and five dependent measures of performance (backward reversible moves, looping moves, solution path changes, returns to start state, and counterintuitive moves). Univariate analyses were not reported unless the overall multivariate model (Hotelling’s Trace) was significant. The differences between the two groups’ performance as assessed by the categorical variables (solved and solution) were measured using a chi-square test.

To assess the differences between performance due to lesion location, a MANCOVA with the following design was employed: one between-subjects factor of group [four levels: no lesion (NCs), LFLs, RFLs, and FFLs], three covariate factors (age, education, and sex), and five dependent measures of performance (backward reversible moves, looping moves, solution path changes, returns to start state, and counterintuitive moves). Univariate analyses were not reported unless the overall multivariate model (Hotelling’s Trace) was significant.

**Correlations to Volume Loss, Intelligence, General Memory Function, and Tower Of Hanoi Performance**

We used Spearman’s $r$ to correlate lesion size, intelligence, memory index scores (WMS), and mean total Tower of Hanoi scores (see Goel & Grafman, 1995) to the measures of Water Jug performance that were not normally distributed. We employed Pearson’s $r$ to correlate these measures and “ratio of counterintuitive moves.” We employed two-tailed tests, as we had no predictions regarding the direction of any significant correlations to performance. Intelligence scores (verbal IQ, performance IQ, and full IQ) were included for both NCs and FLLs using either the WAIS-R scores, WAIS-III scores, or predicted IQ scores from the NART. A Bonferroni correction (lowering alpha to .00278) was applied to minimize the likelihood of Type I error.

**Correlations to Left Prefrontal Cortex Damage**

To localize possible left hemisphere frontal lobe regions critical to successful performance, we used a point biserial correlation. Frontal lobe regions were defined as follows: dorsolateral (BA 8, 9, 10, 44, 45, and 46), ventromedial (BA 11 and 12), and cingulate (BA 24). For each region, we divided patients according to whether a left hemisphere lesion was present in that region. Note that these classifications were made without regard for the patient’s overall categorization as left unilateral, right unilateral, or bilateral (e.g., a bilateral patient might be classified as having only right ventromedial damage). We then compared the performances of the (1) unilateral left hemisphere lesion and (2) unilateral right hemisphere lesion groups on the dependent measures of performance listed above. For each region of interest, a Bonferroni correction was applied (lowering alpha to .00833) to minimize the likelihood of Type I error.

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