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ARE THE FRONTAL LOBES IMPLICATED IN "PLANNING" FUNCTIONS? INTERPRETING DATA FROM THE TOWER OF HANOI

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Abstract—Twenty adult patients with lesions in the prefrontal cortex were tested on the Tower of Hanoi puzzle. The performance of patients was significantly worse than that of controls. This difference could not be accounted for in terms of a general decline in intelligence or memory, or by the size of the lesion. The results further suggest that both patients and controls used the same general strategy to solve the problem and that patients' difficulties with the task have little to do with planning or "look ahead" deficits (as is generally assumed in the neuropsychology literature). Patient performance is best explained in terms of an inability to see or resolve a goal–subgoal conflict. This interpretation is compatible with several existing accounts of frontal lobe dysfunction that postulate a failure of inhibition of a prepotent response to explain poor performance on the Wisconsin Card Sorting task, the Stroop task, the Antisaccade task, the A-Not-B task, and the Delayed Alternation task.

Key Words: frontal lobes; planning; Tower of Hanoi.

INTRODUCTION

Much current theorizing implicates the frontal lobes in "planning" functions [12, 13, 29, 32, 34]. The evidence comes from both, informal anecdotal observations by physicians and clinicians [16, 23] and laboratory experiments. The most famous and influential of the anecdotal stories is probably Penfield's [23] report on the behavior of his sister 15 months after the removal of her right frontal lobes:

> One day about 15 months after the operation, she had planned to get a simple supper for one guest (W.P.) and four members of her own family. She looked forward to it with pleasure and had the whole day for preparation. This was a thing she could have done with ease 10 years before. When the appointed hour arrived she was in the kitchen, the food was all there, one or two things were on the stove, but the salad was not ready, the meat had not been started and she was distressed and confused by her long continued effort alone. It seemed evident that she would never be able to get everything ready at once. . . .
>
> Although physical examination was negative and there was no change in

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> personality or capacity for insight, nevertheless the loss of the right frontal lobe had resulted in an important defect. The defect produced was a lack of capacity for planned administration. . . . (p. 131)

Such observations are certainly compelling. However, the experimental data, and its interpretation, leaves something to be desired. Much of it has (apparently) come from the Tower of Hanoi task. In fact, the Tower of Hanoi is widely used as an experimental and diagnostic tool in the neuropsychology literature to gauge problem solving abilities. It is considered to be especially sensitive to frontal system dysfunction [14, 19, 25] and has become a staple in the evaluation of patients with frontal lobe lesions along with the Wisconsin Card Sorting task, the Stroop task, the Antisaccade task, the A-Not-B task, and the Delayed Alternation task.

The Tower of Hanoi has been administered to many patient populations, including retarded children and adolescents [3, 20, 33], cerebellar patients [14], Fragile X syndrome patients [19], Huntington's Disease patients [2], schizophrenics [10, 27] and traumatic head injury cases [18]. There is, however, a surprising lack of patients with focal frontal lesions among these patient populations. In fact, the only Tower of Hanoi study in the literature involving patients with focal frontal lesions seems to be Glosser and Goodglass [6]. But even in this study, only a small subset of the patients have focal frontal lesions, and the authors report only on the number of moves and rule violations, and they restrict the task to a three-disk problem. All of these studies interpret the Tower of Hanoi as a planning task and go on to impute "planning" or "frontal" deficits when performance difficulties arise.

The majority of problem solving studies involving patients with frontal lesions have actually used Shallice's [28] Tower of London puzzle [22, 28]. Shallice and others have considered the Tower of London to be an easier problem than the Tower of Hanoi, but presumably isomorphic to it. As a result, most neuropsychological studies claiming that frontal patients have difficulty with the Tower of Hanoi task actually cite the Tower of London studies. This is unfortunate because as we will indicate below, the two tasks are quite different.

The goals of this paper are threefold. First, we want to add to the literature data on the performance of patients with frontal lesions on the Tower of Hanoi task. Second, we want to argue that the results warrant no clear conclusions about "planning" or "look ahead" functions. Third, we will suggest that patient performance on the Tower of Hanoi is best explained by postulating a goal–subgoal conflict resolution difficulty.

We present data from a study involving 20 patients with lesions in the prefrontal cortex. As a group these patients were clearly impaired in their ability to solve the Tower of Hanoi puzzle. In an attempt to ascertain why, we took the analysis one step further and examined subjects' solution paths through the problem space. Our findings indicate that the source of patient difficulties can be traced to a failure to see or successfully resolve a goal–subgoal conflict. The interpretation we offer is independent of the standard interpretation given to the Tower of Hanoi in the Neuropsychology literature, which implicates "planning" or "look ahead" abilities. It is, however, consistent with theories of frontal lobe dysfunction that postulate a failure of inhibition of a prepotent response to explain patients' poor performance on the Wisconsin Card Sorting task, the Stroop task, the Antisaccade task, the A-Not-B task, and the Delayed Alternation task [4, 11, 25]. Our results and interpretation extend the scope of these theories to encompass the Tower of Hanoi data and also raise some questions about the nature and power of these theories.

METHODS

Subjects

Twenty patients, all with lesions to the prefrontal cortex participated in the study. In eight patients the lesions were confined to the right hemisphere; in six they were confined to the left hemisphere. Six patients had bilateral damage. The size and location of the lesions within the prefrontal cortex varied, as did pathological histories. Twelve of the patients were Vietnam War Veterans with penetrating missile wounds; one was a closed head injury trauma case; three were tumor removal cases; three were stroke cases; and one suffered from a chronic cystic lesion. All patients were seen 7 months to 25 years after injury and/or surgery. Twelve patients were on anti-epileptic medication (Dilantin = 7, Tegretol = 4, Phenobarbital = 1), three were on medication for mood disorders (Lithium = 1, Imipramine = 2). The involvement of specific structures and brain volume loss for each patient, as determined from MRI, along with etiology are specified in Tables 1(a) (b). These patients were matched for age and education with 20 normal volunteers. This information, along with IQ and memory scores and volume loss measures for patient subgroups, is displayed in Table 2.*

Tower of Hanoi task

The Tower of Hanoi is a puzzle consisting of three pegs and several disks of varying size. Given a start state, in which the disks are stacked on one or more pegs, the task is to reach a goal state in which the disks are stacked in descending order on a specified peg. There are three constraints on the transformation of the start state into the goal state. (1) Only one disk may be moved at a time. (2) Any disk not being currently moved must remain on a peg. (3) A larger disk may not be placed on a smaller disk.

We used a computerized version of the Tower of Hanoi task developed for the US Military Personnel Assessment Battery [24, 26]. It is potentially a five-disk problem. In the manner administered it consisted of a series of nine randomly generated problems of varying difficulty. However, in each case, the largest disk was on the bottom of the middle peg, and the goal state was to stack all the disks in descending order on the middle peg (see Fig. 1). Once generated, the set was fixed and administered to each subject in the same sequence.

The computer screen displayed a picture of the five disks arranged on the three pegs and subjects moved disks by pressing the keys on the keyboard corresponding to the number of the peg. For example, the sequence '1' followed by '2' moved the top most disk on peg 1 to peg 2. The sequence '3' followed by '1' moved the top most disk on peg 3 to peg 1, etc.

The experimenter read and explained the instructions to the subjects and made sure that they understood. Each subject was given two practice trials. After the practice trials the nine test problems were administered. Each subject received the same set, in the same sequence. Each problem had a time limit of 120 sec.

Response measurements

The computer program kept track of a number of measures, including problems solved, number of moves, backward moves, errors, response time, and completion times. It also computed a composite measure called "Score". The Score is a function of accuracy, completion time, problem difficulty, and a range constant. It is adjusted into a z-score using a mean and standard deviation calculated from the scores of several hundred normal subjects.

$$\text{Score} = \text{Accuracy} \times \text{Speed} \times \text{Problem Difficulty} \times \text{Range Cont.}$$

Accuracy ranges from 0 to 1 and is computed by the following formula:

$$\text{Accuracy} = \frac{\text{MinMov} - (\text{NumErr} + \text{NumRver})}{\text{ActMov} - (\text{NumErr} + \text{NumRver})} \times \frac{\text{MinMov} - \text{MovLeft}}{\text{MinMov}}.$$

MinMov: Minimum number of moves required to solve the given problem.

ActMov: Actual number of moves made by the subject. If the actual number of moves is less than the minimum number of moves, then the actual number is set to the minimum number.

NumErr: Number of illegal moves. An illegal move occurs when a subject attempts to place a larger disk on top of a smaller disk.

NumRver: Number of reversal moves. A reversal move occurs when a subject undoes a previous move.

MovLeft: Number of moves remaining to reach the goal state. If the subject successfully completes the task, the number of moves left is set to 0.

The speed is a function of the time the subject spends on the problem (TotalTime), and the maximum time (MaxTime) allotted for the trial (120 sec). The square root function ensures that the effect of the time factor on the performance score will not be as great as the effect of the accuracy factor. If the computed time factor falls below 0.2, it is set at 0.2.

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*The Wechsler Adult Intelligent Scale—Revised (WAIS—R) and Wechsler Memory Scale—Revised (WMS—R) scores were only available for 18 patients. The total brain volume loss measures were available only for the Vietnam War Veterans.

Table 1(a). Loss profile of Vietnam Veteran patient population (as determined from MRI)*

Patients	Frontal lobes		Other areas		Etiology	Vol. loss (cc)
	Left	Right	Left	Right		
J.F.	10, 11, 32, 47 White matter				Penetrating head injury	18.53
S.H.	9, 10, 11, 32, 44, 45, 46 White matter		CC-G Parietal (43) Limbic (24, 32)		Penetrating head injury	62.30
B.S.	9, 10, 32, 44, 45, 46 White matter	Medial (10, 32) White matter	CC-G Parietal (1, 2, 3, 43) Limbic (24, 25, 32) Basal ganglia Corona radiata	CC-G Limbic (24, 25, 32)	Penetrating head injury	77.56
G.B.	10, 11, 24, 25, 32, 47 White matter	4, 6, 9, 10, 11, 24, 25, 32, 45, 46, 47 White matter	CC-G	CC-G Temporal (20, 21, 28, 35, 36, 38) Parietal (43)	Penetrating head injury	123.10
R.B.	10, 11, 24, 32 White matter	9, 10, 11, 44, 45, 46 White matter	CC-G Limbic (24, 25, 32)	CC-G Limbic (9, 24, 25, 32) Basal ganglia Corona radiata	Penetrating head injury	71.95
G.C.B.	Medial (6, 8, 9, 10, 32) White matter	6, 8, 9, 10, 32 White matter	Parietal (4) Limbic (24, 32)	Parietal (1, 2, 3, 4) Limbic (24)	Penetrating head injury	41.70
E.H.	6, 8, 9 White matter	8, 9 White matter	Parietal (1, 2, 3, 4) Limbic (24, 32) Corona radiata	Parietal (4) Corona Radiata	Penetrating head injury	55.12
L.R.	6, 8, 9, 10, 46 White matter	6, 8, 9, 46 White matter	Limbic (24, 32) Corona radiata	Limbic (24, 36) Corona radiata	Penetrating head injury	34.84
R.H.		8, 9, 46 White matter		CC-G Parietal (1, 2, 3, 4) Limbic (24, 32) Corona radiata	Penetrating head injury	30.4
E.J.		9, 10, 32, 44, 45, 46 White matter		CC-G Limbic (24, 32)	Penetrating head injury	25.71
D.J.	9, 10, 11, 32, 46, 47 White matter		CC-G Basal ganglia Insula	Temporal (20, 21, 36, 38)	Penetrating head injury	N/A

*Numbers refer to Brodmann's Areas.
CC-G = Corpus Callosum, Genu.

Table 1(b). Loss profile of non-Vietnam Veteran patient population (as determined from MRI)

Patients	Frontal lobes		Other areas		Etiology	Vol. loss (cc)
	Left	Right	Left	Right		
D.Gv.		Lateral			Tumor	N/A
R.R.		Gyrus rectus			Cyst	N/A
E.A.	Dorsolateral				Tumor	N/A
C.W.	Ventral/medial				Stroke	N/A
D.G.	Frontal horn of lateral ventrical				Closed head injury	N/A
J.H.		Ventral/medial		Temporal	Stroke	N/A
P.F.	Dorsomedial			Parietal corpus callosum	Tumor	N/A
J.M.		Anterior			Stroke	N/A
D.A.		Lateral through to medial medial		Parietal corpus callosum	Penetrating head injury	N/A

Table 2. Characteristics of patient and normal control populations (S.D.)

	Normals	Right Hem	Left Hem	Bilateral	All patients
N	20	8	6	6	20
Age (years)	43.50	44.38	42.50	46.13	44.40
	(13.01)	(13.75)	(10.58)	(1.37)	(11.62)
Education (years)	15.21	15.25	14.67	13.00	14.40
	(2.18)	(3.99)	(2.34)	(1.10)	(2.92)
WAIS—R (IQ)					
General		110.29	92.33	94.83	99.74
		(15.41)	(12.04)	(5.27)	(14.30)
Verbal		111.29	93.00	94.83	100.32
		(15.49)	(11.17)	(7.31)	(14.86)
Performance		106.14	93.17	95.67	98.74
		(16.18)	(12.61)	(9.63)	(12.46)
WMS—R					
General		109.14	83.40	100.17	99.00
		(13.91)	(16.91)	(9.64)	(19.19)
Verbal		109.33	89.17	101.67	100.06
		(13.14)	(16.04)	(10.56)	(17.02)
Visual		104.17	85.40	98.83	96.76
		(11.14)	(11.87)	(10.25)	(14.64)
Volume loss (cc)		28.08	40.41	67.38	54.12
		(3.35)	(30.95)	(31.93)	(23.45)

$$\text{Speed} = \sqrt{1 - \frac{\text{TotalTime}}{\text{MaxTime}}}.$$

Problem Difficulty adjusts the score to account for the relative level of problem difficulty, as follows:

$$\text{ProblemDifficulty} = 0.8 + \frac{\text{minMov}}{15}.$$

Range Constant: This constant stabilizes the range for the point score

$$\text{RangeConst} = 2000.$$

Score Adjustment: After being computed as described above, the score is standardized (i.e. converted to a z score) to allow performance levels to be contrasted across different tests. The Mean and Standard Deviation (S.D.) in the adjustment formula are based on empirical data collected from a population of college students. The formula is as follows:

$$\text{ScoreAdjustment} = \left[\frac{\text{Score} - \text{Mean}}{\text{S.D.}} \times 200\right] + 1000,$$

where Mean = 1114; and S.D. = 254

If the subject fails to solve the problem, he will automatically get a score of 300. If he solves the problem quickly, and with a minimum number of moves he will receive a score in the neighborhood of 2000. If he solves the problem, but takes the maximum amount of time and/or generates many superfluous moves he may well get a score in the 300 range. We found the Score to be a much more sensitive measure of performance than simply tracking whether the problem was solved or not solved as most other studies have done.

In addition to the measures tracked and calculated by the computer, the experimenter manually kept track of the specific moves made by the subjects. This information was used to reconstruct subjects' problem spaces. We will return to this very important construct below.

FIRST-LEVEL RESULTS AND DISCUSSION

The first basic finding is that the controls perform significantly better (M = 1323.1, S.D. = 552.0) than patients with frontal lobe lesions (M = 889.4, S.D. = 634.2),

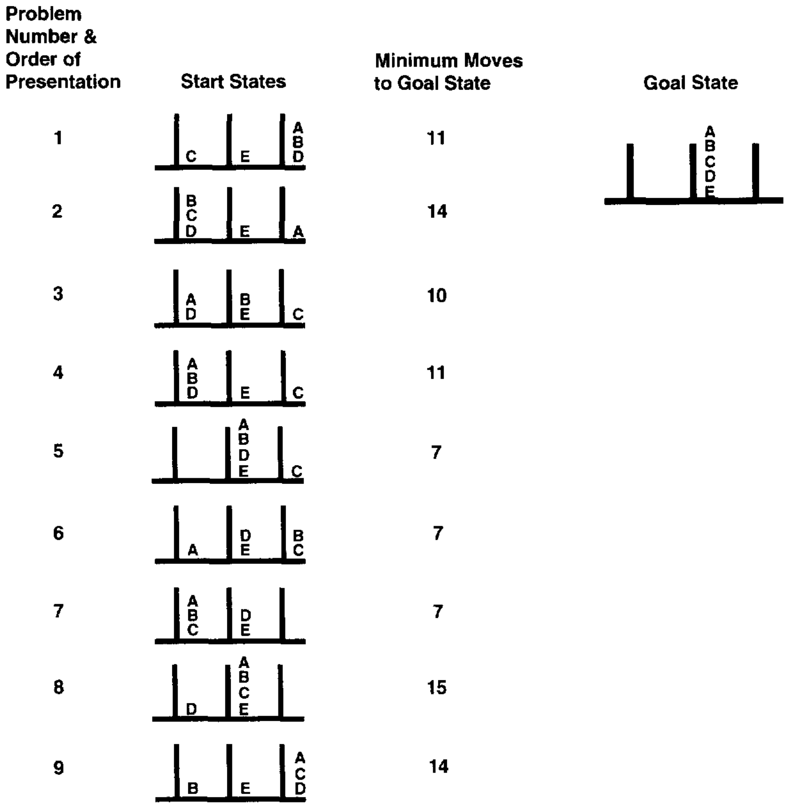

Fig. 1. Tower of Hanoi problems, in the sequence administered.

[$F(1, 304) = 17.97$, $P = 0.0001$]. The performance of the two groups on the set of nine problems (ordered by increasing difficulty) is graphed in Fig. 2. Performance differences across the nine problems are significant [$F(8, 304) = 47.98$, $P = 0.0001$] and the interaction between subject groups and problem difficulty [$F(8, 304) = 1.93$, $P = 0.06$] borders on significance. This interaction is seen more clearly in Figs 4–7 and the underlying factors are discussed in the accompanying text.

When the patient population is subdivided into right, left, and bilateral hemisphere subgroups, the mean subgroup scores are M = 899.7 (S.D. = 655.2), M = 849.3 (S.D. = 633.0), and M = 915.8 (S.D. = 616.5) respectively (see Fig. 3). The control scores are higher than patient subgroup scores (M = 1323.1, S.D. = 552.0). There is still a significant main effect of subject groups [$F(3, 288) = 5.7$, $P = 0.003$] but Fisher's Protected LSD indicates that the performance difference between the patient subgroups is not significant ($P = 0.78$ for left vs right, $P = 0.73$ for left vs bilateral, and $P = 0.93$ for right vs bilateral). The same test shows that performance differences between normal controls and each patient subgroup are significant ($P = 0.004$ for left vs controls; $P = 0.004$ for right vs controls; and $P = 0.01$ for bilateral vs controls). Again, there is a significant interaction between subject groups and problem difficulty [$F(24, 288) = 1.7$, $P = 0.02$], which is seen more clearly in Figs 4–7 and the underlying factors are discussed in the accompanying text.

The above results confirm the widely held belief that patients with frontal lobe lesions are

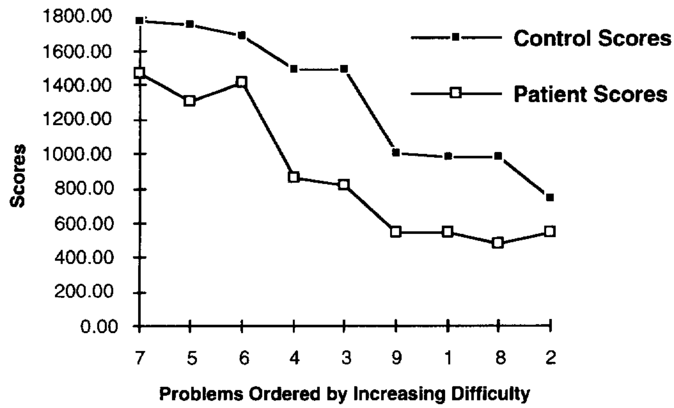

Fig. 2. Patient and control performance scores on the nine Tower of Hanoi problems ordered by increasing difficulty.

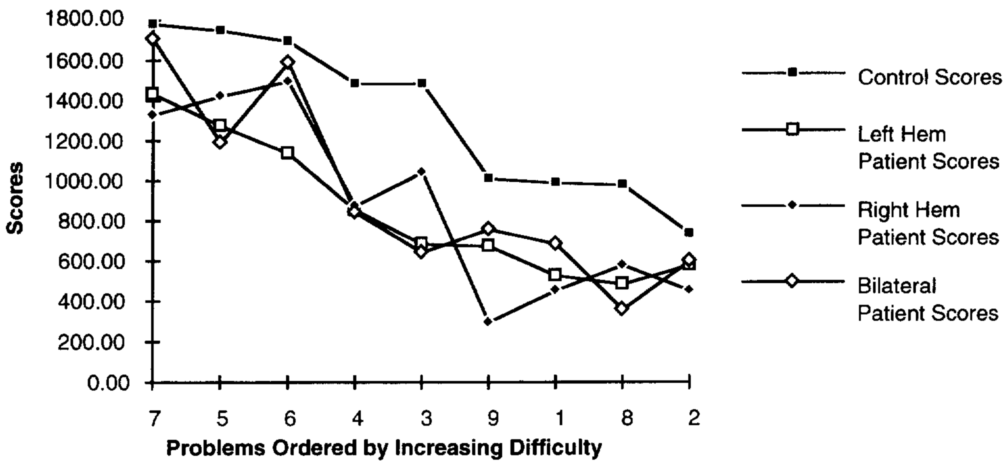

Fig. 3. Patient and control performance by patient subgroups.

impaired on the Tower of Hanoi task with respect to normal controls. However, such a conclusion is only a first step. What we really want to know is whether they are *especially* impaired, more so than on other cognitive tasks. And if they are so impaired, we want to know *why*? To answer the first of these questions we can turn to patient scores on some standard tests (see Table 2). There are two relevant pieces of information in these scores. (1) The overall score of the patients is within the average range, though a little on the low side. (2) The scores of the right hemisphere patients are considerably higher than the scores of the left hemisphere and bilateral patient subgroups, and overall quite respectable.

Both the fact that, as a group patients' scores are in the average range, and that the disparity between the scores of right and left hemisphere and bilateral patients do not result in significant differences in performance, point to the conclusion that patients with frontal lobe lesions are especially impaired in the Tower of Hanoi task.* There are several additional pieces of evidence supporting this conclusion.

First, if we divide up the patient population into halves, by either high and low IQ scores, or high and low memory scores (see Table 3), there are still significant main effects of subject subgroups [$F(2, 296) = 8.8$, $P = 0.0008$ for IQ scores and controls, and $F(2, 296) = 8.7$, $P = 0.0008$ for memory scores and controls]. But Fisher's Protected LSD tests show that the differences between the low and high IQ and low and high memory patients are not significant ($P = 0.85$ and $P = 0.97$ respectively) but that differences between normal controls and high IQ and high memory patient groups are significant ($P = 0.002$ for both). In the case of IQ, the interaction between subject groups and problem difficulty borders on significance [$F(16, 296) = 1.64$, $P = 0.06$] while in the case of memory, it does not [$F(16, 296) = 1.20$, $P = 0.24$].

Table 3. Scores of patient subgroups (S.D.)

Subject subgroups	Mean values	Mean ToH score
NCs	N/A	1323.1 (552.0)
Hi IQ patients	110.00 (11.1)	902.9 (635.4)
Low IQ patients	88.30 (6.1)	875.8 (636.3)
Hi memory patients	110.00 (9.2)	886.5 (626.9)
Low memory patients	86.70 (13.0)	892.3 (644.9)
High volume loss	78.00 (26.7)	994.4 (226.0)
Low volume loss	30.24 (8.8)	980.0 (432.8)

Second, if we divide the Vietnam Veterans ($n = 10$), for whom we have accurate volume loss measurements, into high and low volume loss groups (see Table 3), we find neither a significant difference in the Tower of Hanoi performance of the two subgroups [$F(1, 64) = 0.004$, $P = 0.95$] nor an interaction between subgroups and problem difficulty [$F(8, 64) = 0.777$, $P = 0.62$].

Third, there is little or no correlation between individual patient scores on the Tower of Hanoi and volume loss measurements and IQ and memory scores on the WAIS—R and WMS—R (see Table 4). Curiously, younger patients, and patients with fewer years of education, seem to perform a little better on the Tower of Hanoi than older patients, and patients with more education. This result does not hold for the control group where the correlations between Tower of Hanoi scores and age and education are negligible ($r = 0.077$, $r^2 = 0.006$ for age and $r = 0.121$, $r^2 = 0.015$ for education). There was also a reasonable degree of correlation between patient performance on the Wisconsin Card Sorting task and Tower of Hanoi. We will return to this point in the concluding discussion. However, importantly, in none of the cases is the slope of the regression line significantly different from zero. These additional considerations suggest that the poor performance of frontal lobe patients cannot be fully accounted for by diminished IQ and memory scores and/or size of the lesions.

*However, a word of caution is in order. We did not have a control group of nonfrontal patients. Therefore we cannot rule out the possibility that similar results may be found with nonfrontal patient populations.

Table 4. Correlations between Tower of Hanoi scores and other measures

	R	R^2
Volume loss	0.002	0.000005
Age	0.335	0.112
Education	0.252	0.064
WAIS—R (IQ)		
General	0.106	0.011
Verbal	0.011	0.0001
Performance	0.239	0.057
WMS—R (Memory)		
General	0.159	0.025
Verbal	0.109	0.012
Visual	0.133	0.018
WCST		
Category errors	0.349	0.122
Perserverative errors	0.365	0.133

While interesting, this analysis does not tell us why patients are impaired in the Tower of Hanoi. They certainly license no conclusions about "planning" abilities at this point. To isolate the source of patient difficulty we need a model of how the Tower of Hanoi puzzle is solved and what computational resources are required. Fortunately the Tower of Hanoi is one of the most extensively studied and well understood puzzle problems in the cognitive literature [1, 17, 30, 31] and well-developed models exist. We examine these before continuing with the second level of analysis.

Model and strategies for solving the Tower of Hanoi puzzle

The best developed models of how the Tower of Hanoi is solved are constructed within Newell and Simon's [21] Information Processing Theory. The key theoretical notions for understanding and describing problem solving processes within the theory are the *cognitive system*, the *task environment*, and the *problem space*. The *cognitive system* is a relatively under constrained information processing system consisting of sensory receptors, motor effectors, memory systems (long-term, short-term and external), and a central processing unit. The cognitive system brings two crucial constraints to any task: the limitations of short-term memory (STM) and sequential processing. The *task environment* is the external evironment, inclusive of the problem, in which the cognitive system operates. A *problem space* is a (psychologically real) computational modeling space forged by the interaction of the task environment and the cognitive system. It is specified in terms of states, operators, evaluation functions, and search strategies. Problem solving is viewed as a search through a state space in this framework.

For our nine problems, the start and goal states are specified in Fig. 1. The intermediate states are all possible states generated by the application of legal operators (i.e. all legal transformations of the start state). There are several possible conceptualizations of operators. At the most simple level, it is just the concept of moving a disk from one peg to another (respecting the three constraints noted above). Other more useful concepts are discussed below along with search and solution strategies. Evaluation functions measure the "goodness" of any given state both locally and globally.

There are a number of well-known strategies for solving the Tower of Hanoi puzzle. We summarize each briefly and leave the reader to consult Simon [30] for further details. Simon identifies and describes four strategies for solving the Tower of Hanoi: the goal-recursion strategy, two perceptual strategies, and a "move-pattern" strategy. What makes the analysis interesting is that each strategy requires different concepts, perceptual tests, and computational resources to execute.

Goal recursion strategy. Given *n* disks on the *source* peg, the strategy works as follows: (i) move n-1 disks to the *other* peg, (ii) move the *n*th disk to the *target* peg, (iii) move the pyramid (which is now on the *other* peg) to the *target* peg. But given the problem constraints only (ii) is a legitimate elementary move; (i) and (iii) are themselves Tower of Hanoi problems with one less disk than the original problem. Thus they can be solved by decomposition into the same three steps. This decomposition would continue until $n = 2$. The strategy is elegant, powerful, and guaranteed to find the shortest path through the problem space. However, it requires the concept of moving a pyramid of disks, in addition to moving single disks. Furthermore, it has no perceptual tests associated with it, but it requires maintaining a goal-stack of depth *n* in STM. Also it is not an easy strategy to discover unless one has some understanding of recursion.

Move-pattern strategy [30]. On odd numbered moves, move the smallest disk. On even numbered moves, move the next smallest exposed disk. If the total number of disks is odd, move the smallest disk from the *source* peg to *target* peg to *other* peg, to *source* peg, etc. If the total number of disks is even, move the smallest disk in the opposite direction, from *source* to *other* to *target* to *source*, etc. The strategy requires the concept of odd/even moves and the idea of cycling a disk through the pegs in a particular order. The perceptual tests are quite simple: location of smallest and next smallest exposed disks and differentiating between *target source* and *other* pegs. The strategy also makes the fewest computational demands, requiring only the retention of move parity in STM and is therefore very easy to implement. However, it is an unreasoned strategy—it just works—and therefore is very difficult to discover.

Perceptual strategies. There are two perceptual strategies. The simple perceptual strategy is the most obvious and "natural" strategy. It can be applied at any point but does not lead to the shortest solution path. In its simplest form, it is primarily stimulus-driven, makes few demands on STM memory, and does not require the discovery or execution of arcane rules. The primary concept required is that of the "largest disk blocking the movement of a given disk". The strategy is the following:

(1) if all *n* disks are placed on the target peg, stop; else
(2) find the next disk (i) to be placed on the target peg
(3) if there are smaller disks on top of disk *i*, clear them
(4) clear disks smaller than *i* off the target peg
(5) move disk *i* to the target peg
(6) go to 1.

In this form the perceptual strategy is transparent and easy to execute. Because it is queuing from the current disk configuration at each cycle, it does not make any demands on STM (at least in terms of goal stacks). There are, however, several complicating factors. The first complication, noted by Simon [30], is that if there are four or more disks in the problem, then clearing the *source* peg to move disk *i* will block the *target* peg, and clearing the *target* peg will block the *source* peg, resulting in an infinite loop. The way to overcome this difficulty is to retain a stack of subgoals in STM, marking certain moves as temporary, and interrupting the strategy at certain times to undo them before proceeding.

A second complication is what one might call the goal–subgoal conflict resolution issue. A counter-intuitive, backward move, which superficially/locally takes you away from the goal, is required to achieve the goal. That is, one needs to differentiate between local subgoals and the global goal and acknowledge a conflict between the two, and at certain times inhibit the global goal and be guided by a local subgoal.

For example, in a 3-disk problem, where all the disks are stacked on peg P1 at the start state, and the goal state is to stack all the disks on P3, the globally correct first move (and the most natural move) is to place disk 1 on peg P2, because peg P3 needs to be kept clear for disk 3. If disk 1 is placed on Peg 3 it will need to be moved off before disk 3 can be placed, so why not place it on P2 to begin with? However, if we begin by placing disk 1 on P2, then the only place to put disk 2 is P3. Unless we wish to reverse moves at this point, the next move must place disk 1 from P2 to P3. This clears P2 to accept disk 3. But it was P3 on which we wanted to place disk 3! The correct first move in this situation is to place disk 1 on peg P3, despite the fact that it violates the global goal and will need to be moved again. Locally, it is the correct thing to do.

Simon [30] also describes a more sophisticated version of the Perceptual Strategy which differs from the above in that, if in step 3 an obstructer disk has to be cleared from the source peg, establish a subgoal of moving the obstructer to the other peg (i.e. neither source nor target of disk i) and then recurse through steps 1–3.

In the Introduction we mentioned that the Tower of Hanoi is often considered equivalent to the Tower of London. There are certainly a number of superficial similarities. The Tower of London is also a disk arrangement problem. There are three pegs of varying length and three different colored disks. One peg accommodates all three disks, one accommodates two disks, and the last accommodates one disk. Given a certain starting arrangement of disks on the pegs, the task is to transform the start state into a specified goal state. Shallice [28] does not explicitly specify the constraints on the transformation function, but presumably they are the following: (i) only one disk may be moved at a time, and (ii) any disk not being currently moved must remain on a peg. However, there seem to be no constraints on the order in which disks can be stacked during intermediate states. The absence of this latter constraint, and the fact that the pegs accommodate different number of disks, makes the Tower of London a very different problem from the Tower of Hanoi. None of these strategies that will solve the Tower of Hanoi puzzle will solve the Tower of London puzzle. More generally, the Tower of London does not require recursion, the maintenance of a subgoal stack, not does it require the counterintuitive backward move.

SECOND-LEVEL RESULTS AND DISCUSSION

It was noted that we recorded the individual moves of each subject and used this information to trace subjects' paths through the problem space. These tracings were used to infer subjects' strategies. Strictly speaking, strategies can be unambiguously differentiated only if information regarding subjects' goals/subgoals is available [5]. This information was not available. We had access only to subjects' solution paths through the problem space. However, given these tracings it is in many cases possible to differentiate the perceptual strategy from the goal recursion and move-pattern strategies. The tell-tale signs are deviations of the solution path from the optimal path at certain specific points. Where such deviations are present we assumed the subject was using the perceptual strategy. Where

Table 5. Strategies used by subjects

	Strategies	
	Perceptual (%)	Ambiguous (%)
Normal Controls	79	21
FL patients	83	17

no deviations, or other deviations are present, we make no claims about what strategy is or is not being used.

Sixty problem space tracings were analyzed in this manner. The basic result from the analysis of moves is that both normal controls and frontal lobe patients use the perceptual strategy (see Table 5).

To provide support for this assertion we present several performance measures consistent with the perceptual strategy, but not the other strategies. First, the actual moves vs minimum moves ratio for subjects who solved the problems is less than 100% (85.9%) and there are no significant differences between patients (84.9%) and controls (86.2%) [$F(1, 56)=0.072$, $P=0.80$]. This suggests that the strategy being used does not result in the shortest path and that this same strategy is being used by both subject groups. The reader will recall it was the perceptual strategy that did *not* result in the shortest path.

Second, each group of subjects were subdivided into three subgroups corresponding to low performers, medium performers, and high performers based on their total mean scores. The problems were also subdivided into three groups based upon normal control scores: easy problems ($n=3$), medium problems ($n=3$), and hard problems ($n=3$). The results for normal controls are presented in Fig. 4. There are significant differences [$F(2, 34)=128.9$, $P=0.0001$] in performance between the easy, medium and hard problems, and more interestingly for present purposes, a significant interaction [$F(4, 34)=5.5$, $P=0.002$] between problem difficulty and subject performance levels.

An examination of the three problem groups reveals that the easy problems are all three-disk problems (No. 5, 6, 7), while the medium and hard problems are four-disk problems.* The perceptual strategy predicts just such a qualitative difference between three-disk and four-disk problems—recall the requirement of maintaining a subgoal stack for problems with four or more disks. The goal recursion strategy requires a goal stack throughout and does not predict the interaction. The move-pattern strategy does not require a goal stack for any of the problems and also does not predict the interaction.

So there is considerable evidence to suggest that both controls and patients are using the same strategy. In fact, if patient and control scores for unsolved problems are discounted, there is no difference in the performance of patients and controls [M = 1590.4 (S.D. = 302.5) for controls and M = 1568.8 (S.D. = 370.2) for patients] [$F(1, 56)=0.82$, $P=0.08$].† This suggests that when patients do solve the problems they do as well as controls, however, they more often fail to solve the problems. Why should this be the case? What abilities, resources, and concepts does the perceptual strategy require that subjects are having difficulty with?

First, the concepts and perceptual tests required by the perceptual strategy—e.g. the

*Problem No. 5 becomes a three-disk problem with the removal of the top two disks from the middle peg.
†In fact, in eight of the nine problems, patient scores on solved problems are as high or higher than control scores.

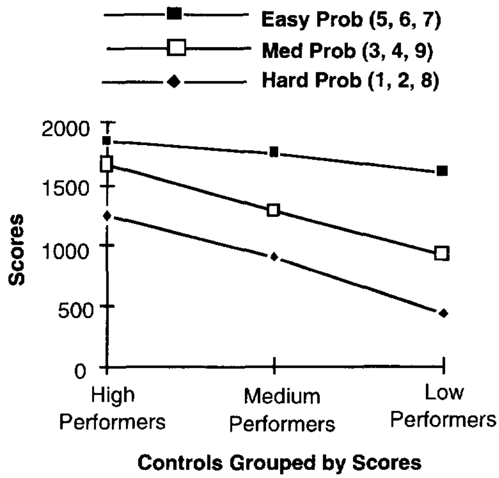

Fig. 4. Performance of control subgroups on easy (5, 6, 7), medium (3, 4, 9), and hard (1, 2, 8) problems.

largest disk blocking the movement of a given disk, and the biggest disk not yet placed on the target disk, respectively—are quite trivial. Patient performance on other tests indicates that such perceptual discrimination and simple concept formation is not an issue for our patient population. More serious candidates for accounting for patient and control performance differences are the requirement of maintaining a subgoal stack in STM and the counterintuitive backward move required for successful completion.

Performance results for normal controls and patients, divided into high, medium, and low performers are graphed in Fig. 5. The main effects of subjects (patients and controls) and subgroups (high, medium and low performers) are both significant [$F(1, 34)=72.1$, $P=0.0001$ and $F(2, 34)=69.9$, $P=0.0001$, respectively] but the interaction is not [$F(2, 34)=1.2$, $P=0.33$]. In this form the results implicate both the requirement of maintaining a subgoal stack in STM and the counterintuitive backward move. It would be desirable to factor them out.

It is not possible to contrive a situation (using the perceptual strategy) where the counterintuitive backward move is not required. However, if the problems are restricted to three disks, it is possible to discount STM requirements. Figure 6 shows performance results for normal controls and patients, divided into high, medium, and low performers solving the easy (three-disk) problems. The relevant information in the graph is the following: The main effects of both subjects (patients and controls) and subject subgroups (high, medium and low performers) are significant [$F(1, 34)=23.3$, $P=0.0001$ and $F(2, 34)=27.9$, $P=0.0001$, respectively]. The interaction is also significant [$F(2, 34)=9.4$, $P=0.0006$]. As maintenance of a subgoal stack in STM is not an issue in the three-disk problems, the patients' poor performance can be attributed to an inability to see and/or resolve the counterintuitive backward move. This suggests that the failure to see and/or resolve the goal–subgoal conflict is a special problem for the patient population.

A comparison with Figs 4 and 6 provides further support for this assertion. The data in Fig. 4 suggests that normal controls' failure to attain perfect scores across problems of varying difficulty can probably be attributed to losing track of the subgoal stack. This becomes the limiting factor as n reaches three disks and continues to increase. The patients'

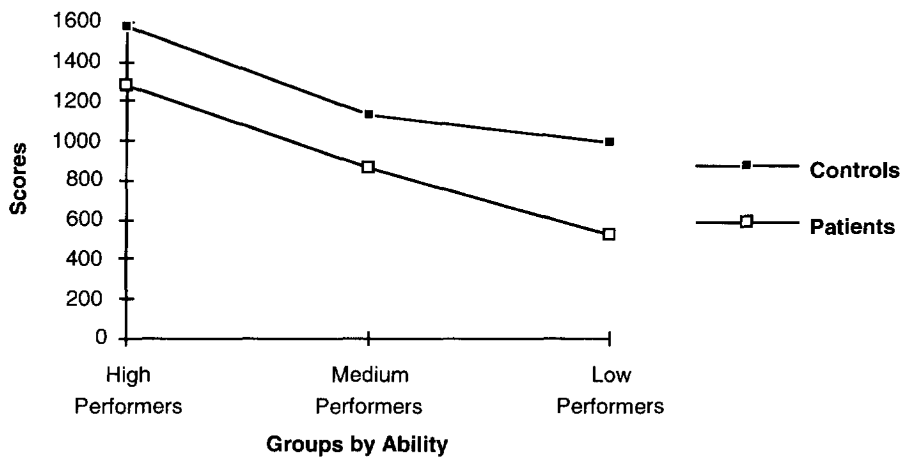

Fig. 5. Performance of subgroups of controls and patients on all problems.

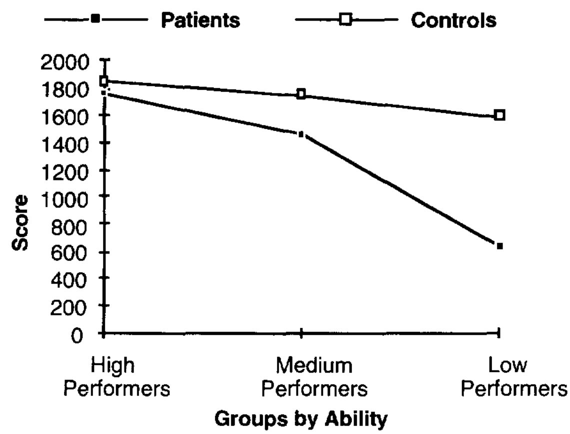

Fig. 6. Performance of control and patient subgroups on three-disk problems (5, 6, 7).

problem is much more immediate, being apparent in the three-disk task, where subgoal retention is not an issue. Figure 7 shows the effect of goal retention on patients. (Both the main effects of patient subgroups and problem difficulty are significant [$F\,(2, 34) = 32.7$, $P = 0.0001$ and $F\,(2, 34) = 91.7$, $P = 0.0001$ respectively], as is the interaction [$F\,(4, 34) = 5.1$, $P = 0.002$]. These considerations suggest that subgoal retention is a problem for patients, but it may be no more of a problem for patients than for controls. The goal–subgoal conflict issue may be the key to understanding poor patient performance.

GENERAL DISCUSSION

It is quite standard in the neuropsychology literature to explain performance deficits in the Tower of Hanoi task as "planning" deficits [14, 19, 28, 29, 33]. The rational underlying the conclusion seems to be that, to successfully complete the task, subjects need to "look ahead"

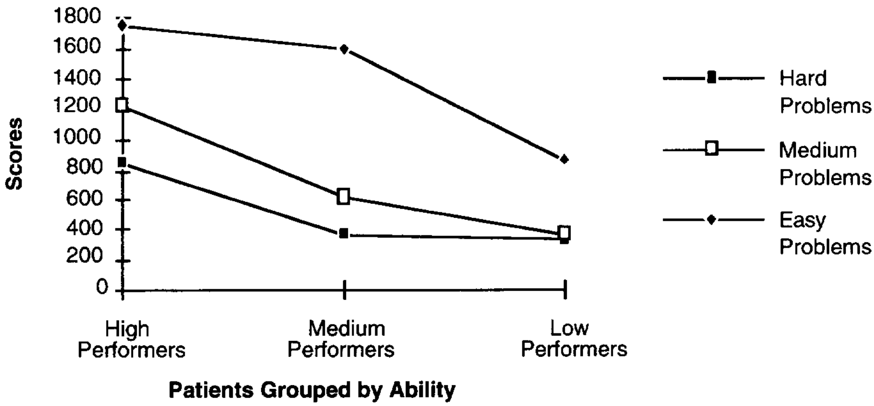

Fig. 7. Performance of patients on three-disk and four-disk problems.

several levels deep and solve the problem in their heads, before physically moving any disks. If they are unable to solve the problem, it follows they were incapable of searching through the moves in their heads, and therefore they must have a "planning" or "look ahead" deficit.

We have offered an explanation that does not implicate "planning" or "look ahead" abilities. There are several ways to view our interpretation. It can be viewed as equivalent to the planning claim, a refinement of the claim, independent of the planning claim, or a refutation of it. Which position one takes depends on what one reads into the "planning" claim.

The term "planning" has been used very loosely in the cognitive and neuropsychology literatures. For some authors it means little more than thinking or problem solving [15]. Other authors have failed to differentiate between constructing and executing or following a plan [28]. On these loose interpretations, every cognitive activity involves planning, and our explanation—along with every other explanation—can be viewed as equivalent to, or a refinement of the existent claims.

We think planning (i.e. the construction of a plan) is a distinct cognitive activity, akin to design, and deserves careful characterization. It has received this elsewhere [7–9]. For our present purposes, the crux of the matter is the following: To plan is to chart a course from point A to point B, without "bumping" into the world. All the "bumping" must be done in some modeling space, and some satisfactory path extracted. Once the path has been constructed, the planning component is complete. The execution or following of a plan is quite a different process. It is the construction and evaluation of this path in some modeling space that we are referring to when we use the term "planning".

If this is what one means by planning, it is not possible to take our interpretation of the results as equivalent to the planning claims. To begin with, the ability to "look ahead" is neither necessary nor sufficient to solve the Tower of Hanoi puzzle. It is not necessary because it is not required by any of the strategies. All of the strategies noted above, including the perceptual strategy used by the subjects, can be implemented in computer programs. Such programs do not need to search several levels deep into the state space to determine the next move. Planning ability is not sufficient to solve the Tower of Hanoi task because you can look ahead all you like, but unless you see the "trick", the counterintuitive backward move, you won't solve the problem.

It is possible to modify the Tower of Hanoi task so that it has a planning component. The modification requires the addition of the following fourth constraint: once a disk has been moved, that move cannot be undone.* This modified task will have a planning or look ahead component, but the planning will be confounded with the goal–subgoal conflict issue. The fact of the matter is, the planning issue is independent of the goal–subgoal conflict issue. Most real world planning tasks do not have a goal–subgoal conflict component built into them. So, at the expense of repetition, the point is, the way the Tower of Hanoi is routinely administered, it does not have a planning component built into it. It can be modified to incorporate a planning component, but then the planning issue will be confounded with the goal–subgoal conflict issue. Either way, the Tower of Hanoi licenses few conclusions about planning. If one wants to draw conclusions about planning deficits, there are better tasks available.†

Our interpretation of the results are not in direct conflict with the planning interpretations; but neither are they equivalent to, or a refinement of, the planning interpretations. They are independent of the planning interpretations (which we do not think are supported by the task or the data). But our explanation is consistent with another class of explanations that are put forward to explain frontal lobe deficits in a variety of tasks, including the Wisconsin Card Sort, Anti-Saccade, Stroop, A-Not-B task, and the Delayed Alternation task. Each of these are considered classic prefrontal tasks and have been explained in terms of the inability of patients to inhibit a prepotent (but inappropriate) response in favor of an alternative (appropriate) response.

As noted by Roberts *et al.* [25], in the Wisconsin Card Sorting Test, the prepotent response is to sort by the previously successful category, while the alternative response is to sort by the new category. In the Stroop task, the prepotent response is to read the word, while the alternate response is to identify the color of ink. In the A-Not-B task the prepotent response is to search in the food well where food was previously found, while the alternative response is to search in a new location. In the Delayed Alternation task, the prepotent response is to search where the item has been hidden, while the alternative response is to search in the opposite location. In the Antisaccade task the prepotent response is to saccade to the cue, while the alternative response is to saccade away from the cue. To these we can add that in the Tower of Hanoi, the prepotent response is to satisfy the global goal, while the alternative response is to satisfy the local goal. In each case frontal patients have difficulty in inhibiting the prepotent (but inappropriate) reponse in favor of the (appropriate) alternative response.*

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*This suggests that one piece of evidence that may be relevant to the planning issue is the number of reversed or "undone" moves made by subjects. There were no significant differences along this measure across subjects or problems. Interestingly, however, the medium and high performers in both groups, made *more* reversals than the low performers [$M = 1.4$ (S.D. $= 0.8$) vs $M = 1.1$ (S.D. $= 0.7$); [$F(1, 36) = 1.47$, $P = 0.23$]. While not significant, these results are not consistent with the assumption that successful performers do more internal modeling. They are consistent with our claim that the relevant issue is one of seeing the counterintuitive backward move.

†As noted above, the Tower of London lacks these complications. If it is administered with the added constraint that a move cannot be undone, it may incorporate a reasonable look ahead component.

*Recently, Roberts and colleagues [25] have made an interesting connection between theories postulating a failure of inhibition and another class of frontal lobe theories that postulate deficits in STM or working memory [11]. They have suggested that there is an intimate, possibly causal connection, between deficits in STM and failure of inhibition. The conclusion is supported by some elegant data from the Antisaccade task. They found that as they loaded the working memory of normal controls, their performance on the task became indistinguishable from that of frontal patients. While our results do not directly speak to this point, they are not entirely consistent with it. We found that the patients begin to suffer from failure of inhibition in the three-disk task, before the STM requirements are present.

This interpretation of our results fits in nicely with the existing literature and extends the scope of this explanatory framework. It is satisfying when a simple notion offers such breadth of coverage. However, we propose it with caution. There are several genuine worries one might have about this explanatory form. The first concern is that this form of explanation requires an independent way of individuating prepotent responses. If the prepotent response is simply the response that patients often fail to make, the explanation is self-fulfilling. It is plausible that there could be such independent individuation for hardwired perceptual functions (like the ones tested in the Antisaccade task), but one would be hard pressed to make such a case for cognitive functions (like the ones tested in the Tower of Hanoi). In the absence of such individuation it is not clear whether saying that frontal patients fail to inhibit an (inappropriate) prepotent response in favor of an (appropriate) alternative response, has any more substance than saying they often make the incorrect/inappropriate response.

A second concern is that the various cognitive tasks brought under this explanation, Wisconsin Card Sort, Antisaccade, Stroop, A-Not-B task, Delayed Alternation task, and the Tower of Hanoi, differ along a number of dimensions. For example, the time scale for a saccade response is on the order of milliseconds, whereas the time scale for a move in the Tower of Hanoi is on the order of tens of seconds. The former response presumably does not have many intermediate steps—certainly not conscious ones. The latter has many conscious intermediate steps. The way in which the prepotent responses are set up in the tasks also differs greatly. In the Wisconsin Card Sorting task the prepotent response is built up through learning reinforcement. In the Tower of Hanoi, it is a part of the logical structure of the problem. In the Antisaccade task it is a hard-wired response. It is hard to believe that the same mechanism that fails to inhibit a hard-wired (perceptual) reflex in the Antisaccade task also affects the conscious reasoned (cognitive) interaction between goals and subgoals in the Tower of Hanoi task. These considerations suggest that "failure to inhibit a prepotent response" constitutes an overt description of behavior rather than a postulation of an unitary mechanism of some sort.

GENERAL CONCLUSION

Frontal patients are impaired in the Tower of Hanoi task. Their poor performance cannot be fully accounted for by diminished IQ and memory scores, or size of lesions. Nor can performance differences be accounted for by differences in strategies. Furthermore, there is little or no evidence to support the almost ubiquitous interpretation that patients' poor performance on the Tower of Hanoi is a result of deficits in "planning" or "look-ahead" abilities. The point is not that frontal patients do not have planning deficits, but simply that, the Tower of Hanoi task does not warrant any conclusions about planning abilities. An analysis of strategies and examination of the data point to two alternative possibilities, STM deficiencies and goal–subgoal conflict resolution difficulties. The evidence suggests that the latter is a special problem for frontal patients. These findings can be made consistent with a cluster of theories of frontal lobe functioning and extend the scope of these theories to explain frontal patient performance on the Tower of Hanoi.

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