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# PLANNING AND SPATIAL WORKING MEMORY FOLLOWING FRONTAL LOBE LESIONS IN MAN

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**Abstract**—Twenty-six patients with unilateral or bilateral frontal lobe excisions were compared with age and IQ matched controls on a computerized battery of tests of spatial working memory and planning. A computerized test of spatial short term memory capacity revealed no significant impairment in the patients' ability to execute a given sequence of visuo-spatial moves. In contrast, a paradigm designed to assess spatial working memory capacity, revealed significant impairments in the patient group in both possible types of search errors. Furthermore, additional analysis showed that the frontal lobe patients were less efficient than controls in their usage of a strategy for improving performance on this test.

Higher level planning was also investigated using a test based on the "Tower of London" problem [SHALLICE, T. *Phil. Trans. R. Soc. Lond. B.* **298,** 199–209, 1982]. Patients with frontal lobe damage required more moves to complete the problems and a yoked motor control condition revealed that movement times were significantly increased in this group. Taking both of these factors into consideration, initial thinking (planning) time was unimpaired in the patient group although the thinking time subsequent to the first move was significantly prolonged. These data are compared to previous findings from patients with idiopathic Parkinson's disease and are discussed in terms of an impairment of higher cognitive functioning following frontal lobe damage.

## INTRODUCTION

CLINICALLY, patients with frontal lobe damage are often described as lacking initiative and the organizational abilities required for everyday situations [7]. For example, PENFIELD and EVANS [17], described a young housewife with a right frontal lobe tumour who was unable to plan and prepare a family meal but was, nevertheless, perfectly capable of cooking the individual dishes. Experimentally, these disabilities are usually accounted for in terms of deficits in the cognitive processes involved in planning although rather few studies [5, 9, 13, 19] have addressed this issue directly. Furthermore, the tests of planning that they employed had a very strong visuo-spatial component that may have independently contributed to the deficit described.

To overcome these difficulties, SHALLICE and MCCARTHY [20] developed the "Tower of London" test, a series of problems thought to depend more heavily on planning than on spatial processing abilities. In this test, subjects are required to move coloured beads between

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three vertical rods in order to match a goal arrangement. Patients with left anterior cortical pathology were shown to be impaired in the number of moves required to complete this task [20]. However, beyond this preliminary account, there has been little further systematic analysis of this important result.

In the present investigation, a modified version of a computerized Tower of London test [14] was used to study planning in a group of patients with localized excisions of the frontal lobes. The task requires the subject to move an arrangement of coloured balls hanging in "pockets" or "socks" to match a goal arrangement presented at the top of the screen. Task difficulty was manipulated by varying the minimum number of moves required to make the correct match. The number of moves required to solve the problem and the relative contributions of initial and subsequent "thinking" or planning time during the execution of the solution were the performance indices. As the time taken to complete the task is to some extent dependent on movement times, a related "yoked control" condition was employed to measure motor initiation and motor execution times separately over an identical series of single moves.

The Tower of London test requires an active search of possible solutions, placing a significant load on spatial working memory. Subsequently, the problem solution must be held in spatial short term memory and transposed into the appropriate sequence of motor movements, before it can actually be executed. In order to assess the individual efficiency of some of these component processes in frontal lobe patients, two further tests were given. A test of spatial short term memory span based on Corsi's block tapping task [11], provided a simple index of the subject's ability to retain, transpose and finally execute a defined sequence of spatial moves. A self-ordered search task was also employed to measure the efficiency of spatial working memory which has been reported to be impaired in individuals with frontal lobe pathology [18]. The present task differed from that used by Petrides and Milner in that the subjects were not required to remember objects by their specific features, only by their particular locations.

## METHOD

### *Subjects*

The twenty-six patients included in this study had all undergone unilateral or bilateral frontal lobe surgery at the Maudsley Hospital Neurosurgical Unit, London. Three other patients were tested but later excluded from the analysis since examination of their CT scans revealed some damage to sub-cortical structures. Fifteen of the remaining 26 subjects had right-sided frontal lobe excisions among which there were three cases of right frontal lobectomy, three cases where an aneurysm of the anterior communicating artery had been clipped, four cases where a right-sided meningioma had been removed, two cases of arterio-venous malformation removal, two cases of astrocytoma removal and one case where a craniopharyngioma had been removed.

Eight patients had left frontal lobe excisions. Among these there were four cases of unilateral lobectomy, one case of arterio-venous malformation removal, two cases where an astrocytoma had been removed and one case where an intra-cerebral haematoma had been evacuated. The remaining three patients had undergone bifrontal meningioma removal. Examples of the main lesion types for left- and right-sided cases are presented in Fig. 1.

The patient group were tested on average 3 years, 2 months post-operatively (median = 24 months, range = 1 240 months). Fifteen were on anti-convulsant medication at the time of testing and all except two were seen as outpatients.

Twenty-six healthy control subjects were chosen to match the patient group as closely as possible with respect to age and premorbid verbal IQ, as estimated by the National Adult Reading Test (NART) [15]. Five of these volunteers were relatives of patients used in this study, whilst the remainder were drawn from the North-East Age Research panel in Newcastle-upon-Tyne.

A sub-group of 19 of these age and verbal IQ (NART) matched pairs was also assessed on the Comprehension and Vocabulary subtests of the Wechsler Adult Intelligence Scale (WAIS), from which a pro-rated estimate of current verbal IQ was derived.

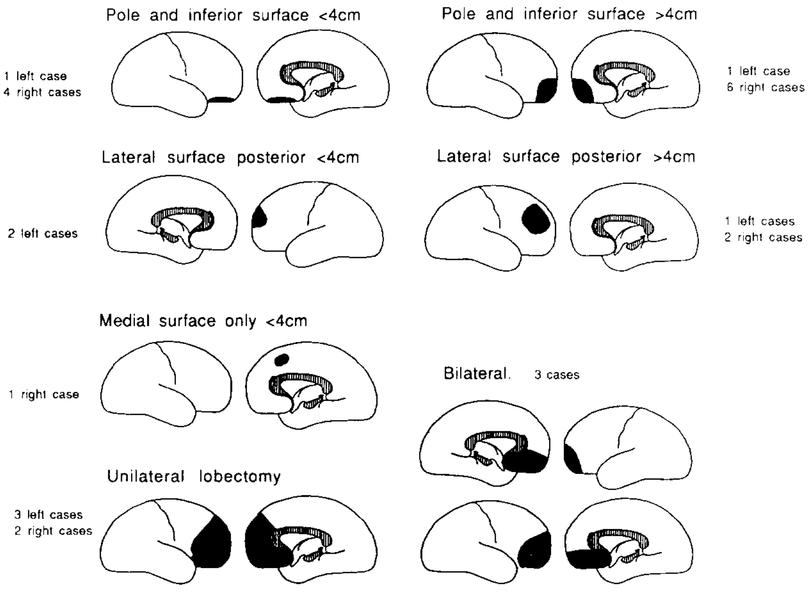

Fig. 1. Diagrams based on the neurosurgeon's drawings at the time of the operation showing the extent of the frontal lobe excision in several representative cases. The blackened areas define the lesion site.

Verbal fluency was also assessed in a separate sub-group of 19 of the frontal lobe patients using the letters F, A and S (each for 1 min), of the Controlled Word Association Test [2], and the category 'animals' (for 90 sec). This measure has previously been shown to be sensitive to frontal lobe pathology, particularly when the damage is on the left side [10]. The performance of the frontal lobe group (mean age = 44.68 years, mean NART IQ = 104.6) was compared to that of a slightly older group of 19 normal control volunteers matched with respect to premorbid verbal IQ (mean age = 59.78, mean NART IQ = 109.9). A summary of the main characteristics for the patient and control groups is presented in Table 1.

One way analyses of variance confirmed that the two groups were well matched in terms of age, $F(1, 50) = 0.09$, estimated verbal IQ (NART), $F(1, 50) = 1.054$, and years of education, $F(1, 50) = 0.767$.

Although several group studies have previously demonstrated that performance on some sub-tests of the WAIS may be sensitive to organic brain damage [12, 23], the frontal lobe sub-group in this study were not significantly impaired in their current (pro-rated) verbal IQ, as estimated from the comprehension and vocabulary sub-tests of the WAIS only, $F(1, 36) = 2.94$.

However, one-way analyses of variance confirmed that there were substantial differences in the verbal fluency scores for the two groups of subjects (Letters F + A + S: $F(1, 36) = 17.26$, $P < 0.01$, Animals: $F(1, 36) = 8.63$, $P < 0.01$), with the patient group's performance being impaired.

### *Materials and procedure*

The main testing procedures were taken from the Cambridge Neuropsychological Test Automated Battery (CANTAB), a series of computerized paradigms run on an Acorn BBC Master micro-computer with a high resolution Microvitec colour monitor and a Microvitec (Touchtech 501) touch sensitive screen. Subjects were seated approx. 0.5 m from the monitor and it was explained that they would have to respond to stimuli by touching the screen.

They were introduced to the apparatus by way of a "motor screening task" in which they were asked to respond to a series of flashing crosses on the screen by placing the index finger of their preferred hand on the centre point of each cross. The finger had to be held in position for 6 sec, at which time the next cross appeared. Following a short demonstration by the experimenter, in which three consecutive crosses were touched, subjects were presented with a series of 10 crosses to touch at 6 sec intervals.

After satisfactorily completing the introductory motor screening task, subjects were given the following three tests in the order described below.

Table 1. Subject characteristics

|  | Age | Sex M:F | Handedness L:R | Education (leaving age) | V. IQ. (NART) | V. IQ. (WAIS) | Verbal fluency |  | Months since surgery |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  | F+A+S* | Animals* |  |
| Patients |  |  |  |  |  |  |  |  |  |
| Mean | 43.03 (3.68) | 14:12 | 2:24 | 16.33 (0.344) | 105.46 (2.53) | 104 (4.71) | 28.2 (2.41) | 17.0 (1.54) | Mean = 3.18<br>Median = 24 |
| Range | 19–73 |  |  | 13–23 | 84–123 | 81–141 | 11–50 | 7–33 | Range = 1–240 |
| Controls |  |  |  |  |  |  |  |  |  |
| Mean | 44.57 (3.47) | 14:12 | 1:25 | 15.75 (1.11) | 108.6 (1.85) | 114.95 (3.78) | 43.05 (2.76) | 23.79 (1.80) |  |
| Range | 16–72 |  |  | 14–23 | 86–128 | 88–141 | 28–70 | 12–47 |  |

*Significant group effects.
Standard errors in parentheses.

### *Spatial short term memory task*

In this computerized version of the Corsi Block Tapping task [11], spatial short term memory capacity was determined from the ability of subjects to remember a sequence of squares on the screen. Each trial began with the same arrangement of nine white 3 cm squares, presented on the screen in a pseudo-random pattern. Subjects were instructed to observe the boxes, as some would change colour one after the other. Their task was to remember the location and the sequential order of the boxes which changed. During each series, one box would change colour for 3 sec, and then return to white before the next in the sequence changed to the same colour. The subject was then prompted by a tone to repeat the sequence by touching the boxes in the same order. During this response sequence, each selected box changed to the same colour for 1 sec, and a feedback tone sounded. Following one demonstration trial by the experimenter, the task began at the simplest level of difficulty with a two box sequence. After each successful trial, the number of boxes changing in the next sequence was increased by one to a maximum of nine boxes. After an incorrect attempt at any particular level, an alternative sequence of the same length was presented. This continued until the subject had failed three consecutive trials at any one level. During each trial, a number in the bottom left hand corner of the screen indicated the length of the current sequence. Also, all boxes changed to the same colour within each series, although on any two adjacent sequences different colours were used to minimize interference. The spatial short term memory span was calculated as the *final* level at which the subject had successfully recalled at least one sequence of boxes.

### *Spatial Working Memory task*

In this task the subject was required to "search through" a number of boxes presented on the screen by touching each one such that it "opened up", revealing what was inside. The object was to collect "blue tokens" hidden inside the boxes and once found, to use them to fill an empty column at the side of the screen. The subjects were instructed that at any one time there would be a single token hidden inside one of the boxes. Their task was to search until they found it, at which point the next token would be hidden. The key instruction was that once a blue token had been found within a particular box, then that box would never be used again to hide a token. Since every box was used once, on every trial the total number of blue tokens to be found corresponded to the number of boxes on the screen. In this task, two types of search error are possible. First, a subject may return to open a box in which a blue counter has already been found (a "between search error"). Second, a subject may return to a box already opened and shown to be empty earlier in the same search sequence (a "within search error"). Subjects could search the boxes in any order, but for control purposes, the number of empty boxes visited (excluding errors) before a token was found was determined by the computer. Thus, each subject received the same degree of feedback prior to the first error. After four practice trials with two boxes, there were four test trials with each of two, three, four, six and finally, eight boxes. The task was scored according to the number of between and within search errors at each level of difficulty.

An efficient strategy for completing this task is to follow a predetermined search sequence, beginning with a particular box and then returning to start each new sequence with that same box as soon as a token has been found. The extent to which this repetitive searching pattern was used as a strategy for approaching the problem was estimated from the number of search sequences starting with the same box, within each of the more difficult six and eight box problems. The total of these scores provided a single measure of strategy for each subject, with a high score (many sequences beginning with a different box) representing low use of the strategy and a low score (many sequences starting with the same box) representing more extensive usage.

### *Planning task*

This task is a variation on one developed by SHALLICE and MCCARTHY [20], based on the "Tower of Hanoi" problem. Two sets of three coloured balls were presented, one in the top half of the screen and one in the bottom half. These were described to the subject as snooker balls since they appeared to be hanging in "pockets" or "socks" (Fig. 2). There were three pockets in each half of the screen, one that could clearly hold three balls, one that could hold two balls, and one that would be completely filled by just one ball. On each trial a red ball, a blue ball and a green ball were placed in predetermined positions in the pockets of each of the two displays. The subject was asked to rearrange the balls in the bottom display, such that their positions matched the "goal" arrangement in the top half of the screen. A ball could be moved by first touching it and then by touching an empty position in one of the other pockets. Once selected, a tone sounded and the rim of the ball began to flash, indicating that it was ready to be moved. At any time, the subject could cancel a selected ball by touching it a second time. "Illegal" moves, such as trying to place a ball high in a pocket when there was no other ball beneath it, or trying to remove a ball while there was another sitting above it in the same pocket, were carefully explained to the subject and if attempted, they were registered, but evoked no response from the computer.

The starting position of the balls was varied such that in any particular trial the solution could only be reached after a minimum of two, three, four or five moves. Subjects were instructed to examine the position of the balls at the beginning of each problem and attempt to solve it in the minimum possible number of moves. This was both given to them verbally and displayed on the screen throughout each trial. They were encouraged not to make the first move until they were confident that they could execute the entire sequence needed to solve the problem. The maximum moves allowed corresponded to twice the minimum number possible plus one, or plus two in the case of "five move"

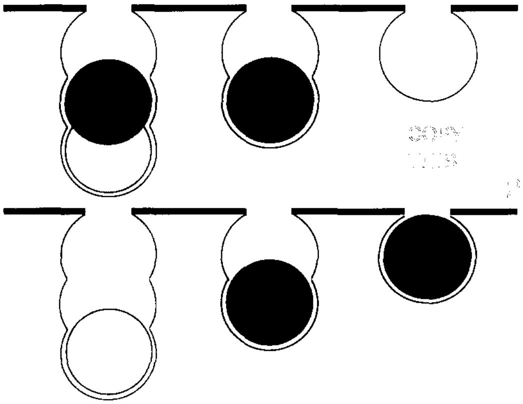

Fig. 2. A sub-problem from the computerized Tower of London test. Two moves (indicated) are required to make the two arrangements identical.

problems. Following successful completion of each problem, the computer gave the word "FINISHED", before moving on the next trial. If the maximum number of moves was reached, "TOO MANY MOVES" appeared before the beginning of the next trial. The program stored the number of moves required by the subject to rearrange the balls and measured the selection and movement latencies for both the first and subsequent moves. After six practice problems with one and two moves, the subject was given two each of two and three move problems and four each of four and five move problems. These test problems corresponded exactly to those used in the original Tower of London test [20].

For each test problem, a "yoked control" condition was employed to provide baseline measures of motor initiation and execution times. On each trial of this control condition, the subject was required to follow a sequence of single moves executed by the computer in the top half of the screen by moving the corresponding ball in the lower arrangement. Thus, initially the two arrangements differed by just one ball. Once the subject had made the appropriate move, the top arrangement changed again so the subject had to make another single move. The test was "yoked" to the main test in the sense that in each trial, the movement of balls was an exact replication of those moved by the subject in corresponding test trial. The measurement of selection and execution latencies in this control condition provided baseline estimates of motor initiation and execution times.

Test trials and "yoked control" trials were arranged in four blocks of six problems each. The first six test trials were given (two problems at each of two, three and four moves), followed by their corresponding yoked control trials. Then the remaining six test problems were presented (two at four moves and four at five moves), followed by their yoked control trials. Between each block change there were two practice trials to ensure that the requirements of the current set of tasks had been fully understood.

### *Data analysis*

The data were analysed using the Statistical Package For The Social Sciences (SPSS) [16]. One- and two-way univariate analysis of variance (ANOVA) were conducted and where appropriate, Pearson product moment correlation coefficients were calculated.

## RESULTS

### *Spatial Short Term Memory task*

The two subject groups were compared with respect to the number of squares that were touched in correct serial order. Mean values and corresponding standard errors for the span measure were 4.96 (0.24) and 5.5 (0.27) for the frontal lobe group and control group respectively. A one-way analysis of variance showed that there was no significant difference in spatial short term memory capacity between the two groups, $F(1, 50) = 2.31$, $P > 0.05$.

### *Working Memory task*

The mean numbers of "between search errors" and "within search errors" made by the two groups within each search set size (i.e. 2, 3, 4, 6 or 8 boxes), are presented in Fig. 3.

The number of within search errors increased significantly with search set size $F(4, 200) = 15.52$, $P < 0.01$ and there was a significant group main effect, with frontal lobe patients making more within search errors than their controls, $F(1, 50) = 6.97$, $P < 0.025$. The group × search size interaction was also significant, $F(4, 200) = 2.62$, $P < 0.05$, which simply reflected the tendency for both groups to make minimal within search errors during the earlier, easy problems. Between search errors also increased significantly with search set size $F(4, 200) = 135.59$, $P < 0.001$ and again, the frontal lobe group made significantly more errors than their controls, $F(1, 50) = 9.86$, $P < 0.01$. The group × search size interaction was significant, $F(4, 200) = 5.25$, $P < 0.001$, reflecting the tendency for both groups to make a minimal number of between search errors during the easier two and three box problems (see Fig. 3).

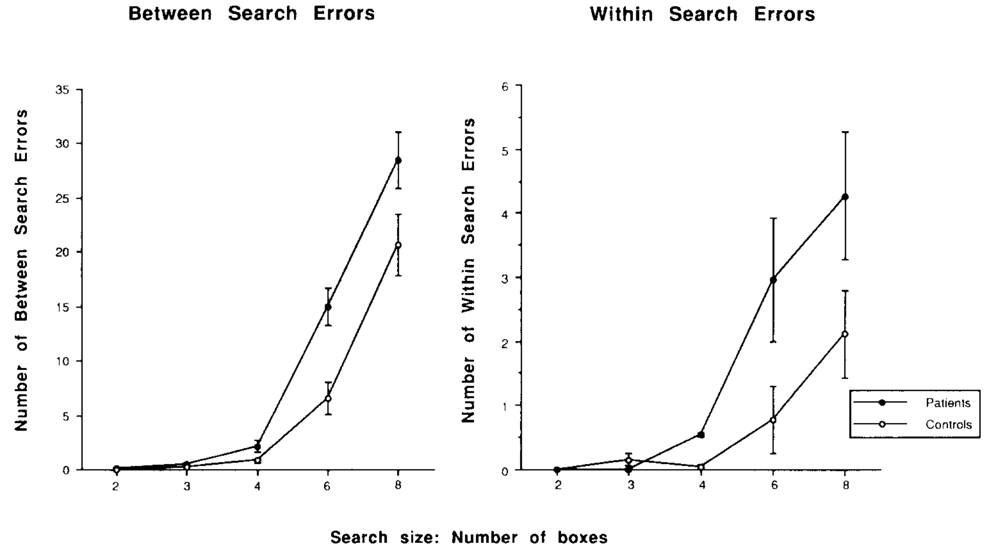

Fig. 3. The incidence of "between search" and "within search" errors on the working memory task. Bars represent SEM.

The measure of strategy employed in this task was scored on a scale of 1–37, with lower scores representing more efficient use of the strategy. The best possible score of 1 was obtained when, within each of the more difficult six and eight box problems, the same box was used to initiate each search sequence. Conversely, if every search within each of these problems started with a different box, the maximum score of 37 was obtained. The mean (+/− SEM) scores for the frontal lobe patients and their controls were 17.58 (0.92) and 14.08 (1.1) respectively. There was a significant difference in the degree to which this strategy was adopted in the two groups, $F(1, 50) = 6.18$, $P < 0.05$. Furthermore, in both the patient and the control groups there was a significant correlation between this strategy measure and the number of between errors on six and eight box problems ($r = 0.61$, $P = 0.001$, $r = 0.76$, $P < 0.001$ respectively). These results indicate that both groups of subjects made more within and between search errors as the number of boxes to be searched increased. Furthermore, frontal lobe patients made more of both type of search error, particularly during the more difficult problems. The frontal lobe group were shown to be significantly less likely than their controls to adopt a search strategy based on a repetitive searching pattern. Furthermore, the number of between search errors made by both groups was significantly related to the extent to which they adopted this particular search strategy.

### *Planning task*

*Number of moves.* Across the 12 test problems, three measures relating to the number of moves required to reach solution were calculated. The "mean number of moves above the minimum possible" provided a general measure of group performance at each level of difficulty. The "proportion of problems solved in the minimum number of moves" provided more specific information about task difficulty, and its effect on the two groups. Finally, the "number of problems solved within the maximum moves allowed", provided a useful index of the subject's ability to solve the problem *per se*, irrespective of the quality of the performance.

Figure 4 shows that the frontal lobe patients took significantly more moves to solve the problems, $F(1, 50)=4.45$, $P<0.05$, and solved significantly fewer problems in the minimum number of moves, $F(1, 50)=5.24$, $P<0.05$. In contrast, there was no group difference in the number of problems solved within the maximum moves allowed, $F(1, 50)=2.41$. In all three cases there was a significant effect of task difficulty. As the problems became harder, the number of moves above the minimum increased, $F(3, 150)=309.54$, $P<0.001$, "minimum move" solutions decreased, $F(3, 150)=64.83$, $P<0.001$, and the number of problems solved within the maximum decreased, $F(3, 150)=40.22$, $P<0.001$. None of the interaction terms were significant. These results suggest that although they were capable of performing the task, the frontal lobe patients were less efficient at solving the "Tower of London" problems.

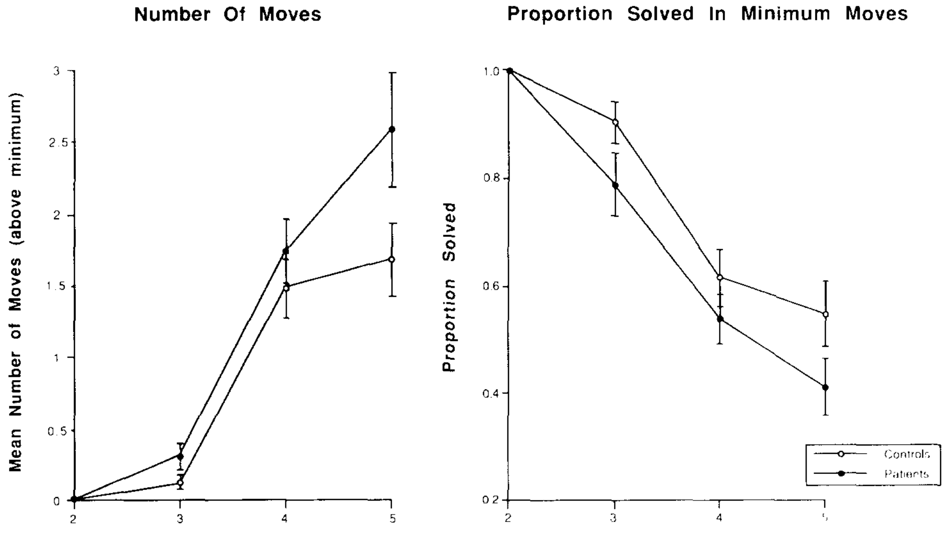

Fig. 4. The Tower of London test: average number of moves and proportion of problems solved in the minimum number of moves as a function of difficulty. Bars represent SEM.

*Movement Times.* Baseline measures of motor initiation and motor execution times were extracted from the 12 "yoked control" trials. The motor initiation time represented the mean time between the onset of each problem, and the completion of the first selection, that is, a correct touch of the required ball. For patients and controls, average initial movement times varied between 2.41–3.4 sec and 1.72–2.60 sec respectively. The motor execution time, was the time between touching the first ball and completing the sequence of single moves that comprise the whole problem. Since these control problems were "yoked" to the test problems, the total execution time was divided by the number of moves to give an estimate of the average movement time per move. Mean motor execution varied between 2.28–2.82 sec (per move) across problems for the patients and between 1.94–2.35 sec for controls. In all cases, latencies were recorded in centisec. and then transformed into logarithms (Base10) to reduce skewness in the distribution. There were significant group differences in both the motor initiation time, $F(1, 50) = 5.82$, $P < 0.025$, and the motor execution times (corrected for the number of moves), $F(1, 50) = 4.60$ $P < 0.05$, with frontal lobe subjects responding at a slower rate in both cases. Also, motor initiation times decreased, $F(3, 150) = 9.73$, $P < 0.001$, and motor execution times increased, $F(3, 150) = 11.18$, $P < 0.001$, as the total number of balls to be moved increased. Although the former trend probably represents a practice effect in both groups, the apparent increase in motor execution time with difficulty most likely results from the way in which this estimate was derived. As the number of balls to be moved increased, so the proportional contribution of initial movement time to the overall problem completion time decreases. Consequently, when the number of moves are taken into account, the movement time (per move) for easier problems will be underestimated to a greater degree than for the difficult problems. None of the interaction terms were significant. Clearly, across all problems, the frontal lobe cases were impaired at both initiating and executing a simple sequence of moves.

*Planning time.* The movement times discussed above were used to derive estimates of planning or thinking time in the main task. Two separate estimates were calculated.

In each problem, the initial thinking time was the time between the presentation of the problem and the first touch, minus the corresponding non-transformed motor initiation time, as calculated from the "yoked control" task. The subsequent thinking time was the time between the selection of the first ball and the completion of the problem minus the total non-transformed motor execution time derived from the corresponding control problem. Any negative values produced by this subtraction were corrected to zero (assuming minimal thinking time), although this was not a common occurrence. Since the subsequent thinking time clearly varied with problem length, this measure was divided by the number of moves to give an estimate of the average thinking time "per move". In this way, pure estimates of initial and subsequent "thinking" or "planning" time were derived unconfounded by motor initiation or execution times. These two measures were independently analysed first for all problems, then including only completed problems and finally including only problems solved in the minimum number of moves. Mean values were calculated within each difficulty level and to satisfy the assumptions of the ANOVA these values were transformed using a logarithmic transformation. The mean initial thinking times for the patients with frontal lobe damage and their controls at each of the four levels of difficulty varied in the range 3.15–15.05 sec and 3.12–11.56 sec respectively. There were no significant group differences in the initial thinking time when all problems were considered, $F(1, 50) = 0.70$, when all completed problems were considered, $F(1, 50) = 0.3$, or when only problems solved in the minimum moves were considered $F(1, 44) = 0.65$. In all three cases there was a significant main effect of task difficulty, $F(3, 150)=28.21$, $P<0.001$, $F(3, 150)=33.01$, $P<0.001$, $F(3, 132)=31.42$, $P<0.001$ respectively. None of the group × difficulty interaction terms were significant.

These results suggest that there was no significant difference between the frontal lobe group and the control group in the amount of thinking time devoted to solving the problem prior to making the first move.

The subsequent thinking times per move for all problems and for problems solved in the minimum number of moves are presented in Fig. 5. In both cases, there was a highly significant group main effect, ($F(1, 50)=7.52$, $P<0.01$ and $F(1, 40)=4.68$, $P<0.05$ respectively), with the frontal lobe group spending more time thinking about the problem subsequent to the first move. The group main effect was also significant when only completed problems were included in the analysis, $F(1, 50)=8.37$, $P<0.01$. There was also a significant main effect of problem difficulty when all problems were considered, $F(3, 150)=33.97$, $P<0.001$, when all successfully completed problems were considered $F(3, 150)=10.72$, $P<0.001$, and when only problems solved in the minimum number of moves were included, $F(3, 120)=3.18$, $P<0.05$. None of the group × difficulty interaction terms were significant.

Although the mean latencies shown in Fig. 5 appear short, it has to be emphasized that these correspond to the time spent thinking *per move*; thus, in a problem of several moves the overall subsequent thinking time may be considerable.

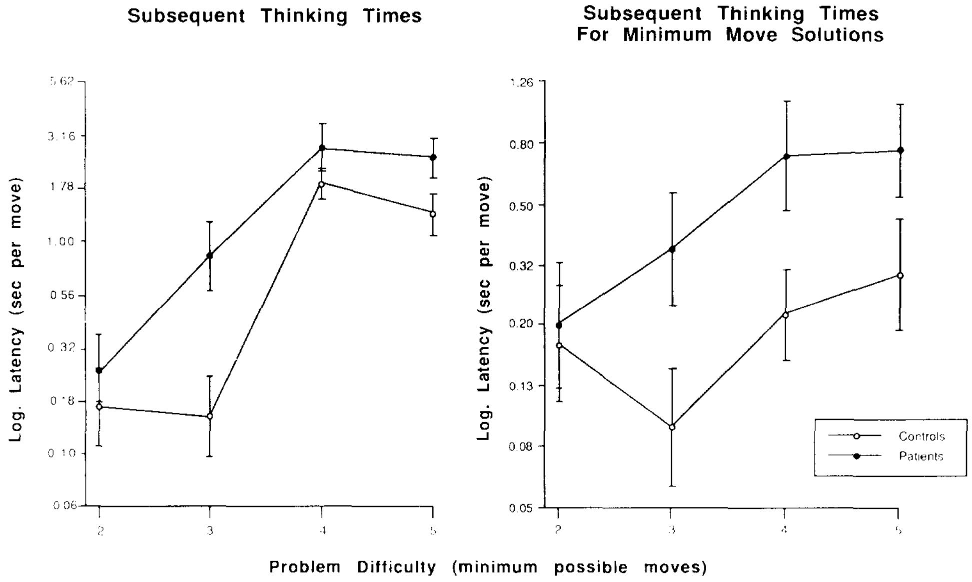

Fig. 5. The Tower of London test: the average thinking (planning) times subsequent to the first move for all solutions and for minimum move solutions. Bars represent SEM

These results show that for all problems regardless of the accuracy of the solution, subjects spent more time thinking after the first move as the test increased in difficulty, even after the number of moves had been taken into account. Furthermore, the frontal lobe group spent more time thinking subsequent to the first move in all cases, whether or not the problem was solved successfully in the mimimum number of moves.

### *Lesion effects*

Following analyses of the group and task difficulty main effects and their interactions, a supplementary analysis was conducted on all data to investigate the effects of laterality, site and size of excision in the patient group. Patients and their matched controls were grouped according to the side of the lesion (2 groups: left ($N=8$), right ($N=15$), only unilateral cases were included), the size of the lesion (three groups: $<4\ \text{cm}^2$ ($N=8$), $>4\ \text{cm}^2$ ($N=10$), complete frontal lobectomy ($N=5$)) and the site of the lesion (three groups: pole and inferior surface ($N=12$), lateral surface posterior ($N=5$), medial surface only ($N=1$), complete lobectomies were excluded). No significant effects of importance were observed.

## DISCUSSION

This investigation has demonstrated that patients with frontal lobe damage are significantly impaired in a computerized version of the Tower of London test, a series of problems requiring higher level planning ability. Although the group with frontal lobe excisions were able to complete even the most difficult problems within the maximum number of moves allowed, they nevertheless required significantly more moves per problem than their matched controls and consequently solved fewer problems in the minimum number of moves. The version of the Tower of London task used in the present study was designed such that planning or "thinking" time could be estimated for each problem, independent of actual movement time for that same problem. Although the two groups did not differ in the amount of time spent thinking prior to the first move, the frontal lobe patients spent significantly more time thinking during the rest of the problem. Thinking times were corrected by taking into account the actual movement times since the latter were in fact, significantly prolonged in the patient group. This finding is consistent with previous literature which has reported slow and apathetic responses in patients with frontal lobe lesions [3, 4, 6, 8]. Similarly, ALIVISATOS and MILNER [1] have recently demonstrated prolonged simple reaction times in a group of frontal lobe patients.

The results of the computerized Tower of London test are consistent with earlier data described by SHALLICE [20], in which a group of patients with "anterior" cortical damage were shown to be impaired in the original version of the task. However, whereas the earlier study reported deficits in left sided anterior patients only, in the current investigation there were no effects of laterality, lesion location or lesion size. Furthermore, a recent study (Shallice, Warrington, Watson & Lewis, in preparation) has failed to replicate the original left frontal lobe deficit (see SHALLICE [21], p. 347). There are several possible reasons for these discrepancies, including differences in the criteria used for patient selection, heterogeneity of aetiology, variability of lesion location and size and differences in the testing procedures and measures employed. Thus, for example, the "anterior" group of SHALLICE [20], included patients with fronto-parietal and frontal-temporal lesions. In contrast, the current investigation only considered cases where the damage was restricted to the frontal lobes.

At the more difficult levels, the Tower of London task requires the non-routine generation and execution of a sequence of spatial moves to solve the problems satisfactorily. However, since several independent cognitive processes are clearly involved in this operation, the precise nature of the frontal lobe deficit on this task is unclear. One possibility is that the frontal lobe patients are impaired at evaluating the problem, and then generating, refining and revising a solution before making the first move. Consequently, this inadequate planning leads to a disorganized solution involving more moves and more time.

Alternative explanations for the impairment in the group with frontal lobe damage may be formulated in terms of the non-planning requirements of the task. For example, frontal lobe patients may be impaired at retaining a sequence of spatial moves in short term memory for a sufficient length of time to allow its successful execution to take place. Alternatively, they may be unable to transpose an accurate cognitive plan into the appropriate motor sequence or unable to execute the motor sequence itself.

None of these accounts seems likely in view of the unimpaired performance of the frontal lobe patients in the test of spatial span. Importantly, these patients were, on average, able to remember and execute a sequence of almost five moves which is, of course, the maximum number required for correct solutions in the Tower of London task. The test of spatial span places a greater load on short term memory than the Tower of London test (having more alternative spatial positions), and both tasks require the transposition and execution of a previously defined sequence of visuo-spatial moves. They differ only in that the Tower of London requires the *production* and *execution* of such a sequence whilst the test of spatial span only requires the *reproduction* of a sequence imposed by the experimenter.

Successful planning in the Tower of London task also places a significant load on spatial working memory, which has previously been shown to be impaired after frontal lobe damage [18]. Working memory is essential not only for the storage of a correct sequence, but also in the search processes required in any analytical problem of this type, by which possible solutions are considered and either rejected or accepted. In the present study, the frontal patients were significantly impaired in a self ordered searching task designed to assess spatial working memory. In searching for goal objects, hidden according to a defined set of rules, they committed more errors both within and between different search sequences. The present study also employed a measure of strategy, based on the extent to which subjects used repetitive search sequences within the more difficult test problems. In both groups, the extent to which the strategy was adopted was positively related to the accuracy of mnemonic performance, presumably reflecting how an efficient strategy can help to reduce the load on spatial working memory. Furthermore, the frontal lobe group was shown to be less efficient in the use of this strategy, raising the possibility that at least some of their impairment in spatial working memory arises secondarily from a more fundamental deficit in the use of organizational strategies, a view consistent with the conclusions of PETRIDES and MILNER [18].

The frontal lobe impairment on the Tower of London test can also be interpreted in terms of the observed strategy deficits in the spatial working memory test. Thus, the use of inappropriate organizational strategies to assess the problem, and then to generate and refine a possible solution may place a disproportionate load on active working memory during the planning phase prior to the first move.

One might expect that inefficient planning would lead to prolonged "thinking" times in the frontal lobe group. However, thinking times in this group were only longer subsequent to the first move. The absence of significantly lengthened initial thinking times in the frontal group implies that these patients make the first move before they have successfully generated an appropriate solution to the problem. STUSS and BENSON [22] have also described the behaviour of frontal lobe patients in complex arithmetical tasks requiring multiple steps as "failing to analyse or execute the component steps required for problem solution". In both cases, this behaviour could be considered to be "impulsive", although the slower movement times among the frontal lobe patients in the present study shows that this "impulsivity" does not simply arise from a tendency to move more quickly.

The performance of patients with frontal lobe excisions described in this study is rather different from that of medicated Parkinson's disease patients, described by Morris *et al.* [14], using a slightly different form of the computerized test battery. Essentially, the difference between the two groups can be described in terms of the increased incidence of errors in the Tower of London and spatial working memory tests in the frontal lobe group which were not evident in the patients with Parkinson's disease [14]. Both of these deficits have been attributed to a similar strategic impairment in the frontal lobe group and it therefore seems likely that a similar impairment is not characteristic of these patients with Parkinson's disease. Conversely, the retardation in "initial", but not "subsequent", thinking time shown in the patients with Parkinson's disease contrasts with the present pattern shown by the patients with frontal lobe damage although it will be important to compare the two groups more directly in future studies. These dissociations between the accuracy and latency of thinking support the view that planning consists of several distinct, though interactive, cognitive components, which may depend upon separate neural substrates. The contrasting results from the patients with frontal lobe damage and Parkinson's disease may also reflect a qualitative difference in performance produced by cortical vs sub-cortical pathology.

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