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Imaging the mental components of a planning task

J.B. Rowe [a,*], A.M. Owen [b], I.S. Johnsrude [a], R.E. Passingham [a]

[a] *Wellcome Department of Cognitive Neurology, University College London, 12 Queen Square, London WC1N 3BG, UK*
[b] *MRC Cognition and Brain Sciences Unit, 15 Chaucer Road, Cambridge CB2 2EF, UK*

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Abstract

The Tower of London task (TOL) has been widely used to assess the ability to plan. We used H_2O^{15}-positron emission tomography to isolate some of the cognitive components of the task. Ten male volunteers were scanned twice in each of six conditions. In two conditions (plan) the subjects had to plan the best solution to TOL problems. In two other conditions (plan–control) the subjects were required to generate four moves without being constrained by a goal. In plan and plan–control tasks the subjects either planned the moves and then executed them (MOVE conditions) or imagined the necessary moves (IMAGINE conditions). The plan and plan–control tasks were matched for the working memory load and 'initial thinking time'. A visuomotor control task and rest served as baseline conditions. Performance on the plan tasks, in contrast to the baseline conditions, was associated with activation in the dorsal prefrontal cortex, premotor and parietal cortex, and cerebellum. Performance of the plan–control tasks was associated with activation of the same areas. Contrasting the plan with the plan–control tasks revealed no residual activation in the prefrontal cortex. These data show that the activity of the dorsolateral prefrontal cortex on the TOL can be accounted for by the components of generating, selecting and/or remembering mental moves. The task of relating the moves to the goal involves a comparison with a representation of the goal in posterior association areas. We did not find evidence that activation of the dorsal prefrontal cortex is specifically related to the evaluation of a path towards a specified goal, a key component of planning.

Keywords: Tower of London; PET; Plan; Prefrontal cortex

1. Introduction

Planning is a complex process essential for normal daily activities. It describes the ability to think ahead and evaluate the consequences of possible actions. In other words to plan is to 'model a sequence of actions in preparation for carrying out a particular task' [47]. A clear operational definition comes from Dehaene and Changeux [4], who define planning as 'the goal-directed, trial-and-error exploration of a tree of alternative moves…When no direct move is available, a move must be generated, tried out, and accepted or rejected depending on its ability to bring the problem closer to a solution'. This highlights the key processes required in planning: to be aware of the goal; to generate possible moves; to make moves mentally; to evaluate these moves with respect to the goal; to reject or select moves; and to hold these moves in memory. This study aims to define the neural correlates of these separate processes in planning.

The 'Tower of London' (TOL) and related Tower of Hanoi tasks have been used to assess planning in clinical populations. The planning demands and problem-solving strategies suitable for these tasks have been reviewed elsewhere [4,13,51] and differences in performance of the two tasks have been reported [17]. The Tower of London has a clearer rating scale for problem difficulty [13] has been widely used to assess planning deficits in patients with neurosurgical lesions [20,37,47], neurodegenerative diseases [38] and psychiatric illness [7,9,35,41].

In the TOL, subjects are presented with two sets of three balls (start and goal arrays), each on three pegs [47] or in three pockets [37]. Subjects must plan how to move the balls on the start array, one at a time, in order to match the goal array. Constraints on valid

* Corresponding author. Tel.: +44-20-78337472; fax: +44-20-78131420.
E-mail address: j.rowe@fil.ion.ucl.ac.uk (J.B. Rowe).

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moves are provided by the different colours of the balls and the different heights of the pegs (or depths of the pockets). Legal moves consist of moving the top ball of any given peg (pocket) to a location on another peg (pocket). Subjects may be required either to make actual moves [37], or express planning ability by specifying the minimum number of moves required [2,40]. Problem difficulty varies from trivial, requiring one obvious move, to extreme, requiring at least nine moves in exact order. With increasing difficulty, moves must be made which do not directly place a given ball in its goal position, but are necessary to permit future moves. Some problems include counterintuitive moves, in which a ball must be moved temporarily out of its goal position, to permit intermediate steps [51]. Patients with prefrontal lesions are particularly poor at problems which demand such counterintuitive moves [33].

Several groups have used functional imaging to determine the neural correlates of planning in the TOL, in both normal subjects and patients. Computerised versions of the TOL have been used in studies with positron emission tomography (PET) and single photon emission computed tomography (SPECT). When planning in the TOL has been compared to visuomotor controls, a consistent distributed network of brain activations has been found. This includes the following areas: the left dorsal prefrontal cortex, left or right premotor cortex, anterior cingulate cortex, bilateral parietal cortex, medial parietal cortex (precuneus), prestriate cortex and midline cerebellum [2,7,32,38,39]. Some of these studies have also observed activation of the right prefrontal cortex [2], and right or left cerebellar hemisphere [2,6]. Further, increased prefrontal activation was seen with more difficult problems [2,39], and in subjects who took longer to plan moves or made fewer errors [32].

Although these studies indicate the network of brain activity required for performance on the TOL, they do not permit an analysis of the contributions of these separate regions to the overall task. In the present study we sought to define the roles of the different brain regions in terms of the constituent cognitive processes of the TOL. Previous studies did not control for the generation, selection and working memory for self-generated moves. We developed control tasks that included these cognitive processes, but lacked a goal, and therefore did not require 'the construction and evaluation of a path from A to B' [13]. These control tasks were matched to the TOL for the generation and selection of moves, the working memory load for moves, and the execution of moves. Control for the working memory of self generated moves was particularly important. Owen et al. [39] showed that working memory for moves specified by the experimenter was associated with activation of prefrontal cortex at least as much as performance of the TOL. However, Deiber et al. [5] have reported that there is more activation of the prefrontal cortex when subjects imagine such externally specified moves compared with self generated (that is, freely selected) moves. Two of our control tasks required self generated moves because on the TOL the subjects also generate their own possible moves. We also included visuomotor and rest baseline conditions to allow direct comparison with the earlier studies.

In the TOL, subjects are asked to determine the solution before executing their moves. In this context, the processes of planning the solution should be the same whether or not the subjects go on to execute the moves. We therefore used a TOL task in which the subjects merely imagined the solution as well as a TOL task in which they also executed the moves. These were compared with control tasks requiring either just imagination or imagination and execution of responses. This created two task pairs, which had in common the presence or absence of a goal. Since the aim of the present study was to identify the components of planning (not just performance of the TOL) we used conjunction analyses to reveal the activation that was common to planning, that is irrespective of the way in which the TOL task was executed.

2. Methods

2.1. Subjects

Ten normal male volunteers were studied, aged 23–34 with a mean of 27 ± 4 years. They had no history of neurological or psychiatric illness, and were not on medication. Ethical approval was given by the Ethics Committee of the Institute of Neurology and permission to administer radioactive H_2O^{15} was given by the Administration of Radioactive Substances Advisory Committee of the Department of Health, UK. The subjects gave written informed consent.

2.2. Presentation of stimuli

The format of presentation resembled the TOL as used by Owen et al. [39], with software written in Visual Basic 6.0 (Microsoft Corporation, USA). The problems were controlled from a personal computer (Gateway computers, Pentium II processor) operating Windows 95 (Microsoft Corporation, USA). The presentation and responses were made using a touch sensitive screen (Vision Master, Liyama Electric Co., Japan).

Two patterns of balls were presented, one above the other. The balls were red, green and blue, resting in three pockets that could hold one, two or three balls respectively. An example of the presentation is shown in Fig. 1. Balls in the lower array could be moved by touching the screen. A ball was moved by touching it

and then an empty pocket. When touched, a ball would be highlighted in yellow until an empty pocket was touched or it was touched again to cancel the move. If an illegal move was attempted, such as moving a ball onto the background, no changes occurred. Subjects then either moved the ball to one of the other pockets or cancelled the move as above. Only the topmost ball in a given pocket could be moved, and pockets could not be 'overfilled'. When a trial was completed, the screen cleared for one second and the next trial began. Up to 16 different trials could be presented without interruption.

Pretraining took place half an hour before scanning. The subjects were familiarised with the presentation format and also with responding on the touch sensitive screen, using 'easy' TOL problems requiring one to three moves. The six conditions were then explained, demonstrated and practised (eight trials maximum) until subjects were confident that they understood each condition. The sets of problems used in pre-training were not used in scanning sessions.

The TOL can be used to present 216 formally distinct problems requiring 0–9 moves to solve, each in six colour combinations. Of these 1296 visually distinct problems, 174 require four moves. One hundred and sixty of these were divided between 10 problem sets, each of 16 trials, to encourage novel planning for each trial. During image acquisition, all problems in plan conditions required a minimum of four moves. Subjects were allowed a maximum of 10 moves or 30 s before the trial ended and the next problem was presented. The trials were presented from 30 s before image acquisition and continued for up to 150 s total duration.

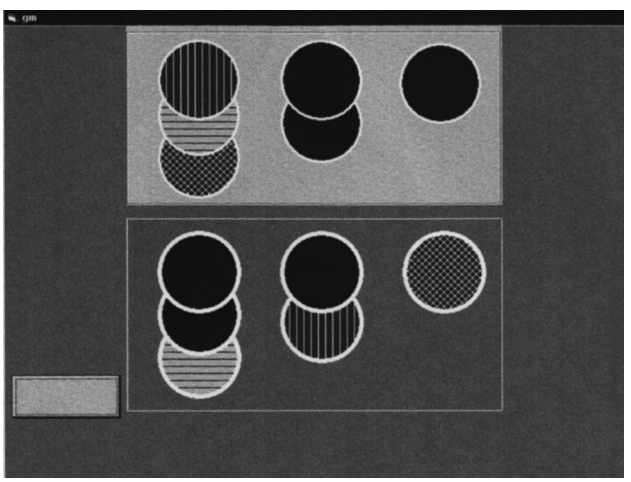

Fig. 1. Example of the screen presentatrion during the PLAN–MOVE task (colour replaced by greyscale). The lower array shows the starting pattern and the top array shows the goal. The solution to this problem requires a minimum of four moves. The button to the left of the display is shown blank, but in the PLAN–IMAGINE condition, it is labelled 'done', to be pressed when subjects have the solution to the problem.

2.3. Experimental design

Twelve sequential measurements of regional cerebral blood flow were made, two each of six conditions. The six conditions included two in which there was a specified goal (PLAN–MOVE and PLAN–IMAGINE), two formally similar but with no goal (PLAN–CONTROL–MOVE and PLAN–CONTROL–IMAGINE), a visuomotor control condition (VMC) and rest (REST).

2.3.1. PLAN–MOVE

The two arrays of balls were initially different. The subjects had to determine the best sequence of moves to change the lower configuration into the top configuration of balls (goal), in the minimum number of moves. They were asked to plan the solution 'in their head' and then 'execute the moves as smoothly as possible' by touching the balls and empty pockets in turn. Before imaging they were reminded to 'think first then move'.

2.3.2. PLAN–IMAGINE

The presentation of problems was similar to PLAN–MOVE. They were again asked to plan the solution 'in their head' However, they were not required to execute the actual moves. Instead, they were asked to press a button on screen to indicate that they had the solution. The screen then cleared for one second and the next problem was presented. To ensure compliance with the imagination task, 'catch trials' were included. These occurred in pretraining, and before the scanning window in the imaging session. On 'catch trials' the screen did not clear after the button was pressed; instead the words 'please show me' appeared and subjects were asked to execute their solution by touching the balls on screen in turn.

2.3.3. PLAN–CONTROL–MOVE

In plan–control conditions, the two arrays of balls were initially the same, so there was no goal to change one pattern to the other. Subjects were asked to think of any four moves on the lower array of balls and, when they knew the sequence of these moves, to execute it smoothly and swiftly. The duration of each trial was yoked to the trials in the prior PLAN–MOVE condition, and the number of moves made matched the minimum number of moves required in PLAN–MOVE.

2.3.4. PLAN–CONTROL–IMAGINE

Two identical arrays were presented and subjects were required to think of four moves that could be made in the lower array. However, they were not to execute these moves, merely to press a button when they knew what these four moves would be. 'Catch trials' were included in pretraining and before the scan-

ning window to ensure compliance. The duration of each trial was yoked to the trials in the PLAN–MOVE condition, and the number of moves made matched the minimum number of moves required in PLAN–IMAGINE.

2.3.5. VISUOMOTOR CONTROL

This was yoked to the PLAN–MOVE condition. The subjects repeated the actual moves made in the PLAN–MOVE condition, one by one, without planning or remembering moves. The two arrays were initially identical. A ball in the top array was highlighted together with an empty pocket. Subjects then touched the ball and the empty pocket in turn, and the ball moved. The next ball and pocket then lit up according to the timing of the moves made in PLAN–MOVE.

2.3.6. REST

The screen showed the two sets of pockets, empty, against the same neutral background. No moves were necessary.

The conditions were presented in a pseudo-random order. There was the constraint that the yoked conditions (PLAN–CONTROL–MOVE, PLAN–CONTROL–IMAGINE, and VMC) had to occur after the plan condition with which they were yoked. However, all conditions occurred both early and late in the scanning session.

2.4. Data acquisition

The behavioural data were recorded by the TOL program in Visual Basic. Data recorded included: the time from trial presentation to first touching a ball; the time taken to make each move; all individual moves made; and the number of error moves in PLAN–MOVE condition. Attempted illegal moves were not recorded.

The subjects lay supine in the scanner. Head movement was reduced by a padded helmet with chinstrap, fixed to the headrest. The screen position was adjusted to give full view of the screen and easy reach by the right arm. The visual display extended across approx. 15 degrees of vision. PET was performed using a CTI ECAT HR plus scanner (CTI, Knoxville, TN, USA) in three-dimensional mode with inter-detector collimating septa removed. The axial field of view was 155 mm providing whole brain coverage including cerebellum.

Regional cerebral blood flow was measured using $H_2^{15}O$. Background activity was counted over 30 s prior to each image. Six to ten milliCuries (mean 8.9 mCi) were delivered over 20 s to the left arm. Image acquisition began 5 s before the rising phase of the count curve, approx. 25 s after injection, and continued for 90 s. Correction for tissue and helmet attenuation was made using a transmission scan from 68Ga/68Ge sources at the start of the scanning session. The inter-scan interval was 9 min.

Corrected data were reconstructed by three dimensional filtered back-projection (Hanning filter, cut off frequency 0.5 cycles/pixel) and scatter correction. Sixty-three transverse planes were obtained with 128×128 pixel image matrix, with a resulting pixel size of $2.4 \times 2.1 \times 2.1$ mm, and a resolution of 6 mm at full width half maximum.

Anatomic structural images were acquired for eight of the subjects on the same day, using a VISION MR scanner at 2 Tesla (Siemens, Erlangen, Germany) with a T1 MPRAGE sequence ($TE = 4$ ms, $TR = 9.5$ s, $TI = 600$ ms, resolution $1 \times 1 \times 1.5$ mm, 108 axial slices.

2.5. Behavioural data analysis

The behavioural data were analysed using Microsoft Excel SR-1 (Microsoft Corporation, USA). The number of moves per trial and the total number of moves made in the scanning interval were calculated for each condition. The mean time taken to initiate movement and complete each trial was calculated for each condition for trials during the scanning interval. Thinking time was the time taken from presentation of the arrays to initiation of the first movement or to pressing the button to indicate that moves had been determined. Thinking times were subjected to a two-factor repeated measures analysis of variance with goal (plan vs. plan–control) and execution (move vs. imagine) as within-subject factors. Catch trials lay outside the scanning interval and were not included in these analyses.

2.6. Imaging data analysis

All analyses of images were made using Statistical Parametric Mapping software, SPM97d (Wellcome Dept Cognitive Neurology, London, UK), in the MATLAB 4 environment (Mathworks, Sherborn, MA) on SUN UNIX Systems (SUN Microsystems, Mountain View, CA). Images were realigned to the first image by rigid body correction for head movements between scans [11]. All images were normalised to a standardised anatomic space [50], by matching each image to a standardised template [16] using linear and non-linear spatial transformations [11]. Each image was smoothed with an isotropic Gaussian kernel (FWHM = 12 mm), to accommodate inter-subject differences in anatomy. The effect of global differences in cerebral blood flow between scans was removed by subject specific AnCova scaling of activity to a nominal mean global activity of 50 ml/100 g/min [12].

There were two analytical models. First, six orthogonal contrasts were specified corresponding to each of the six experimental conditions. We wanted to define

brain regions activated by the presence or absence of a goal, regardless of method of execution (movement or imagination). We therefore used conjunction analyses as defined by Price and Friston [45,46] to identify areas in which there was a common simple main effect of plan versus baseline (analysis 1), plan–control versus baseline (analysis 2), or plan versus plan–control (analysis 3), regardless of whether the solutions were physically executed or imagined. The conjunction analyses were:

analysis 1: [PLAN-MOVE vs VMC]

and [PLAN-IMAGINE vs REST]

analysis 2: [PLAN-CONTROL-MOVE vs VMC]

and [PLAN-CONTROL-IMAGINE vs REST]

analysis 3: [PLAN-MOVE vs PLAN-CONTROL-MOVE]

and [PLAN-IMAGINE vs PLAN-CONTROL-IMAGINE].

For activations to be attributable to the common difference of a plan (analyses 1 and 3) or plan–control (analysis 2), the magnitude of this effect must be similar. In factorial designs, the conjunction may be construed as a main effect in the absence of an interaction (for all our analyses interactions were excluded at $P < 0.05$).

The conjunction analyses were used to test hypotheses about regionally specific conjoint condition effects, producing a statistical parametric map of the t statistic for each voxel. The SPM$\{t\}$ was transformed to a map of corresponding Z values. The resulting foci were characterised by spatial extent, maximal Z value and location of the peak value. The significance of each region after correction for multiple comparisons was estimated by using the theory of Gaussian fields [10]. Results are presented for voxels at which the Z statistic exceeded 3.09 ($P = 0.001$, uncorrected for multiple comparisons).

In the second model, the times taken to make the first move or to press the button indicating that a sequence of moves had been determined (thinking time) in the plan and plan–control conditions were entered as covariates of interest. In analysis 4, data is presented for voxels in which thinking time significantly covaried with activity. Again voxels at which $Z > 3.09$ ($P < 0.001$) were considered significant.

3. Results

3.1. Behavioural results

For the PLAN–MOVE condition, subjects completed a total of 172 trials during imaging (mean 8.6 trials per scan, standard deviation 2.5). Overall performance was good. During the PLAN–MOVE condition 148/172 (86%) of trials were solved in the minimum number of moves. Two subjects were error free. For the 172 four-move problems imaged for PLAN–MOVE condition, the subjects made a total of 700 moves (mean 4.07 moves made per problem). Errors were not made on catch trials, suggesting that subjects were properly imagining the solutions to the problems in PLAN–IMAGINE. In the PLAN–CONTROL–MOVE condition, the subjects made varied patterns of four moves from trial to trial with little repetition. The mean time to first movement (thinking time) was 7.5 s (± 0.7 s) for PLAN–MOVE and 7.3 s (± 0.8 s) for PLAN–CONTROL–MOVE, and the mean time to button press was 8.1 s (± 0.6 s) for PLAN–IMAGINE and 8.1 s (± 0.7 s) for PLAN–CONTROL–IMAGINE. By analysis of variance, there was no effect of plan/plan–control ($F = 0.5$, $df = 1,19$, $P =$ n.s.) or movement/imagine ($F = 1.1$, $df = 1,19$, $P =$ n.s.) in time to first move, and no interaction ($F = 0.9$, $df = 1,19$, $P =$ n.s.).

3.2. Imaging results

3.2.1. Plan versus baseline (analysis 1)

This conjunction analysis identified areas in which the activation was related to planning on the TOL. The contrasts [PLAN–MOVE vs. VMC] and [PLAN–IMAGINE vs. REST] share the common difference of planning the solution to the TOL. Areas of conjoint differences in activation for the task pairs are listed in Table 1. They included the left dorsal and right orbital prefrontal cortex, bilateral dorsal premotor cortex, left motor cortex, parietal, prestriate and inferior temporal cortex, as well as in the insula. Subcortical activations were seen in the cerebellar vermis and hemispheres bilaterally. Fig. 2A shows the distribution of SPM$\{Z\}$ superimposed on a standard T1 MRI image [16] at the left prefrontal, premotor and parietal cortex. The parietal activation lay in or above the posterior part of the intraparietal cortex.

3.2.2. Plan–control versus baseline (analysis 2)

The contrasts [PLAN–CONTROL–VE vs. VMC] and [PLAN–CONTROL–MAGINE vs. REST] share the common difference of generation and selection of moves and memory for selected moves. Areas of conjoint activation for the task pairs are listed in Table 2. There was again activation of dorsal and orbital prefrontal cortex, bilateral premotor cortex and intraparietal cortex. There was also activation of the anterior cingulate cortex and right insula. Subcortical activations were seen in the cerebellar vermis and hemispheres. There were no prestriate or inferotemporal

Table 1
Coordinates of peak significant changes in rCBF in the conjunction analysis 1 [PLAN–MOVE vs. VMC] and [PLAN–IMAGINE vs. REST]

Region of activation	L/R	Brodmann's area	Coordinate			Z-value
			x	y	z	
Dorsolateral PFC[a]	L	9/46	−50	26	42	3.79
Orbitofrontal PFC	R	11	28	30	−28	3.91
Premotor cortex	L	6	−26	−2	50	4.22
	R	6	26	0	58	4.39
Anterior insula	R		34	20	0	4.19
Caudate nuclei	L		−18	−20	16	4.47
	R		18	−12	18	3.44
Intraparietal cortex	L	7	−8	−74	54	6.36
	R	7	14	−70	50	5.50
Medial parietal (precuneus)	R		2	−58	50	4.97
Prestriate cortex	L	18/19	−26	−76	38	3.86
	R	18/19	34	−80	28	3.99
Striate cortex	L	17	−16	−94	24	4.24
Cerebellar vermis	–		0	−56	−24	6.96
Cerebellar hemisphere	L		−40	−56	−36	4.13
	R		38	−66	−26	5.27
	R		54	−56	−40	4.77

[a] PFC = prefrontal cortex.

activations. Fig. 2B shows the distribution of SPM{Z} superimposed on coronal sections through prefrontal, premotor and parietal cortex.

3.2.3. Plan versus plan–control (analysis 3)

The contrasts [PLAN–MOVE vs. PLAN–CONTROL–MOVE] and [PLAN–IMAGINE vs. PLAN–CONTROL–IMAGINE] share the common difference of goal representation and evaluation of moves towards that goal. Areas of conjoint activation differences for the task pairs are listed in Table 3. There was no activation in the prefrontal cortex, but there was activation in the left superior parietal cortex; this lay posteriorly near the back of the intraparietal sulcus. Extensive activations were observed in the prestriate cortex and inferior temporal cortex, as well as in the right premotor cortex. Cerebellar activations were seen in the cerebellar nuclei and right paramedian lobe. Fig. 3 shows the parameter estimates for condition specific effects at the left dorsolateral prefrontal cortex. This illustrates that there was no significant difference between plan and plan–control conditions. Fig. 4 shows the SPM{Z} distribution superimposed on a coronal section through the lingual and fusiform gyri.

3.2.4. Correlation with thinking time (analysis 4)

This analyses looks for the effect of planning time on activations during plan conditions [PLAN–MOVE and PLAN–IMAGINE]. The results indicate those areas in which prolonged thinking time in the plan and plan–control conditions was correlated with greater regional blood flow. There was a single peak of activation in the left frontal pole (-14, 68, 10, $Z = 3.66$, $P < 0.001$).

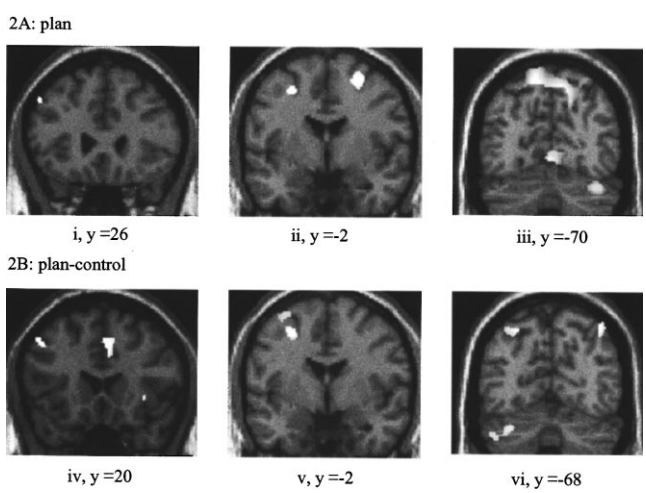

Fig. 2. Significant rCBF increases shown as SPMs for activations during plan (A) and plan–control (B) conditions, each compared with visuomotor and rest baseline conditions. Coronal planes are indicated by the corresponding y coordinate in standard anatomic space and all voxels shown exceed $Z = 3.09$ ($p = 0.001$). the top row, A i–iii, shows areas of significantly greater activation in plan conditions than baseline (analysis 1). Activations shown are: i. left dorsolateral prefrontal cortex; i bilateral premotor cortex; iii. bilateral intraparietal and right inferior temporal cortex. The bottom row, B iv–vi, shows areas of significantly greater activation in plan–control conditions than baseline (analysis 2). Activations shown are: iv. the left dorsolateral prefrontal and right anterior cingulate cortex; v. left premotor cortex; vi. intraparietal cortex.

Table 2
Coordinates of peak significant changes in rCBF in conjunction analysis 2 [PLAN–CONTROL–MOVE vs. VMC] and [PLAN–CONTROL–IMAGINE vs. REST]

Region of activation	L/R	Brodmann's area	Coordinate			Z-value
			x	y	z	
Dorsolateral PFC[a]	L	9/46	−46	20	42	3.99
	R	9/46	36	26	32	4.49
Orbitofrontal PFC	L	11	−30	56	−12	5.48
	R	11	28	54	−12	5.30
Premotor cortex	L	6	−48	−2	50	4.76
	R	6	26	4	58	4.50
Anterior cingulate cortex	L	32	−10	14	48	3.53
	R	32	6	24	36	4.27
Anterior insula	R		34	20	0	3.83
Intraparietal cortex	L	7	−24	−68	50	4.15
	R	7	50	−56	48	5.21
Cerebellar vermis	–		0	−52	−10	5.23
	–		8	−78	−28	4.76
Cerebellar hemisphere	L		−40	−60	−36	4.21
	R		30	−44	−40	3.89

[a] PFC = prefrontal cortex.

4. Discussion

It has commonly been assumed that because patients with prefrontal lesions are impaired on the TOL, and the TOL requires planning, that the prefrontal cortex is critically involved in the process of planning. In the present study we have separated some of the mental components involved in planning, and have shown that the activation of the dorsal prefrontal cortex can be accounted for by the processes of generating, selecting and remembering moves. We have been unable to find evidence that activation of the dorsal prefrontal cortex is related to the presentation of problems in which the subjects must evaluate a path towards a specified goal.

4.1. Planning

We have identified the distributed network of activations during the planning tasks (analysis 1). This network was similar to that observed in previous studies and was activated irrespective of whether the subjects were required to execute their solution or not. There was activation in the left dorsolateral prefrontal cortex [2,7,32,38,39]. The peak lay posteriorly in the dorsal prefrontal cortex, probably in the region identified by Petrides and Pandya [44] as cytoarchitectonic area 9/46. However, there was also a peak of activation at the left frontal pole where the activation increased with longer thinking times (analysis 4). Morris et al. [32] also observed, using SPECT, a similar correlation between thinking time and left frontal activation.

There was activation bilaterally in premotor cortex, parietal cortex and prestriate cortex [2,7,32,38,39], the right insula [2,7,39], ventral temporal cortex and caudate nucleus [7]. We imaged the whole cerebellum and confirmed activation of the midline cerebellum [2,7,38,39] as well as activation in the cerebellar hemispheres [7]. The agreement with earlier work supports our use of conjunction analysis to isolate planning irrespective of the way the task is presented.

The aim of the subsequent analyses was to identify the neural correlates of the mental components of planning. Following Dehaene's definition of planning [4], we can say that the subjects were required to detect and represent differences between the start and goal arrays of balls, to generate possible moves; to select the moves, to mentally make these moves, to evaluate these moves as steps towards the goal, and to hold earlier moves in working memory until the whole solution was known. All of these components are common to the conditions PLAN–MOVE and PLAN–IMAGINE.

4.2. Generation, selection and memory of moves

In order to distinguish between these components we included the plan–control conditions (PLAN–CONTROL–MOVE and PLAN–CONTROL–IMAGINE), which have much in common with the plan conditions. The subjects had to generate moves, select and mentally make these moves, and hold these moves in memory until the whole sequence was determined. However, the plan–control conditions differ in that subjects do not need to think ahead to a particular end-state or goal, nor evaluate moves in the light of such a goal. By goal we mean here a particular target or end-state of balls, rather than the general desire of subjects to comply with experimental procedures.

Table 3
Coordinates of peak significant changes in rCBF for conjunction analysis 3 [PLAN–MOVE vs. PLAN–CONTROL–MOVE] and [PLAN–IMAGINE vs. PLAN–CONTROL–IMAGINE]

Region of activation	L/R	Brodmann's area	Coordinate			Z-value
			x	y	z	
Premotor cortex	R	6	38	6	70	3.36
Intraparietal cortex	L	7	−10	−68	70	3.92
Prestriate cortex	L	18/19	−42	−60	6	4.26
	R	18/19	16	−68	12	4.57
Lingual/fusiform gyrus	L	37	−30	−48	−8	3.53
	R	37	40	−46	−20	3.66
Cerebellar nuclei	L		−4	−56	−24	4.48
Cerebellar hemisphere	R		56	−56	−44	3.36

It could be argued that subjects generated a goal state in mind, and planned the moves towards it. However, debriefing subjects on their understanding and performance of the task suggested that this was not the case: each move was determined on the basis of the start array and previous moves without regard to a self-determined target pattern. The chosen moves determined the end state rather than a chosen end-state determining the moves. Further, it would be very difficult for inexperienced subjects to know whether a self-generated pattern was exactly four moves away from the start array. Trial and error attempts to formulate end-states four-moves away from the starting position would require more than one guess for some trials. Trials would therefore take longer on average than planning the specified four-move problems in plan conditions. The behavioural data show this was not the case.

It is also possible that rather than set a particular goal state in mind four-moves different, subjects may choose a series of intermediate goals, imagining a goal state one or two moves different, then 'planning' to move towards it. Such trivial one- or two-move problems however do not necessarily require planning, because they may be solved by a simple visio-spatial matching strategy without the need to think ahead. In addition, they do not activate the prefrontal cortex in normal subjects [39] and performance is not impaired by lesions of the prefrontal cortex [20,37].

We compared the conditions [PLAN–CONTROL–MOVE vs. VMC] and [PLAN–CONTROL–IMAGINE vs. REST]. The conjunction for these comparisons reveals activations common to both plan–control tasks, that are irrespective of whether the subjects executed the moves or not (analysis 2). There was bilateral activation of the dorsolateral prefrontal cortex, intraparietal cortex and premotor cortex, as well as in the cerebellar vermis and both hemispheres. There were additional activations in the frontal poles and anterior cingulate cortex.

The generation and free selection of movements has been studied previously with functional imaging [24–26]. Jueptner et al. [24] used PET to study the brain areas that were active in the generation and free selection of finger movements, compared either with rest or with repetitive finger movements. Compared with repetitive movements, free movement was associated with bilateral activation in the dorsal and polar prefrontal cortex, anterior cingulate cortex (BA 32), premotor cortex and parietal cortex. The main difference between these results and our own (analysis 2) is that there was no activation in the cerebellum. This difference may be due to the fact that in the present study there was a delay during which the subjects prepared to perform the sequence of moves. In another PET study, Jueptner

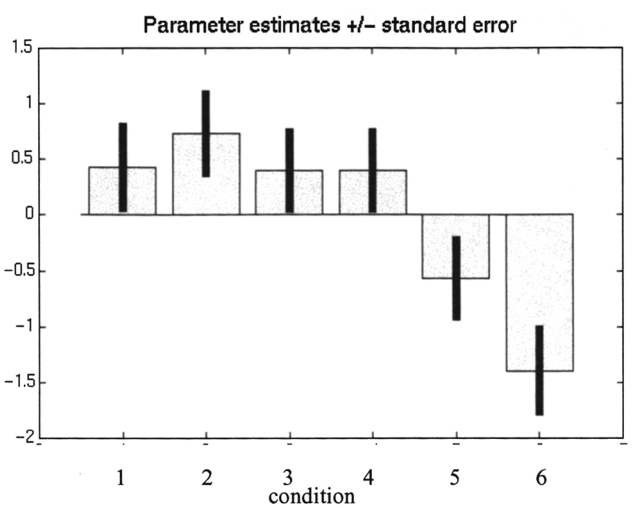

Fig. 3. Parameter estimates for the left dorsolateral prefrontal cortex (−50, 26, 42). The values indicate the parameter estimates within the general linear model of SPM analysis (standardised units) and indicate the relative actvation of that voxel under different task conditions. The six condition effects are: 1. PLAN–MOVE; 2. PLAN–IMAGINE; 3. PLAN–CONTROL–MOVE; 4. PLAN–CONTROL–IMAGINE; 5. VC; 6. REST. The chart indicates that the activation of the left prefrontal cortex does not significantly differ between plan and plan–control conditions (1–4).

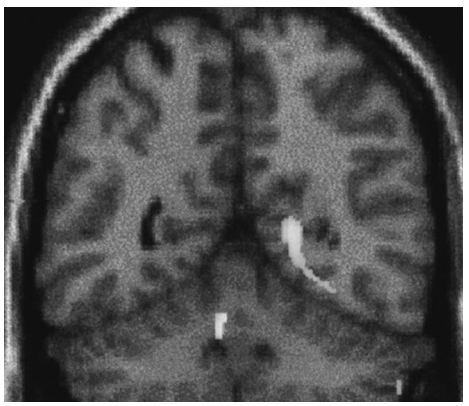

Fig. 4. Significant rCBF increases in analysis 3, shown as a SPM for a coronal section through the plane of $y = -54$, illustrating the activation of the lingual and fusiform gyri when plan conditions were contrasted with plan–control conditions.

et al. [25] compared the brain activations during free drawing and copying drawings. In free drawing, there was greater activation in the left inferior prefrontal cortex (BA 45, 47; $P < 0.001$), and at a lower significance level ($P < 0.01$) in the dorsal prefrontal cortex, cingulate cortex, parietal cortex and insula. Again there was no activation of the cerebellum. Jeuptner et al.'s results suggest that the cerebellum is not activated in the unconstrained generation and selection of movements. The cerebellar activations seen in our study suggest a role for the cerebellum in remembering moves during a delay period.

Working memory for four or five moves in the TOL was studied explicitly by Owen et al. [39]. The subjects were asked to watch while the balls moved, and then reproduce this sequence at the end (an externally ordered working memory task). In comparison with a visuomotor control condition, there was extensive activation of the left dorsal prefrontal cortex (BA 46) as well as bilaterally in the frontal pole (BA 10) and area 9. Thus the dorsal prefrontal cortex can be shown to be activated when subjects generate and select moves, or when they are required to hold moves in memory. The study did not image below the horizontal plane of $z = -22$ mm (Talairach space); but Krams et al. [31] have carried out a PET study in which there was activation in the cerebellar hemispheres when subjects remembered a sequence of targets and prepared to touch them, even when movement was controlled for $(30, -58, -20: Z = 3.32)$.

In the plan and plan–control tasks the subjects also made mental moves: that is, they imagined making the moves that they selected. In making mental moves the subjects could either use internal representations of limb movements, or make saccadic eye movements between the current and desired location, or both. The neural correlates of motor imagery have been studied with PET. Deiber et al. [5] required subjects to repetitively imagine finger moves that were specified by external cues and found activation in the left dorsal prefrontal cortex, anterior cingulate cortex/pre-supplementary motor cortex and parietal cortex. This study did not image the full cerebellum, but Jueptner et al. [26] also compared imagination of freely selected moves in PET and imaged the whole brain including the cerebellum. For imagination of freely selected movements they found activation of the ipsilateral cerebellar vermis and hemisphere at locations below the lowest z plane imaged by Deiber et al. [5].

When subjects make mental moves or remember them they may also make saccadic eye movements and this may facilitate their mental imagery. Subjects make saccades during mental imagery [3] and there is interference between making voluntary saccades and mental imagery [29]. Voluntary saccades also occur during spatial working memory tasks [15].

The role of gaze–control strategies in the TOL has been investigated by video-tracking natural scanning eye movements during the one-touch version of the TOL [14]. After initially reviewing the goal array, normal subjects then look predominantly at the start array, either from ball to ball or at a neutral midpoint in the array, before verifying the solution by looking again at the goal. On more difficult problems the subjects sometimes look back to the goal during the planning period (Hodgson, personal communication). During elaboration of the solution, the pattern of fixations depends on the moves being rehearsed by the subjects. Hodgson et al. [14,15] proposed that the shifts in gaze strategy allow manipulation of information within mental imagery and reduce the working memory load during the TOL.

The use of eye movements to mentally move balls, or to facilitate the memory of moves may explain the activations seen in the occulomotor regions of the cerebellum (posterior vermis and flocculus) when the plan–control tasks were compared to baseline. We did not however identify corresponding activations in the frontal eye-fields. The premotor and prefrontal activations found in analyses 1 and 2 are spatially distinct from the activations identified by functional imaging studies as regions for saccadic control [1,42,43,49].

However, subjects could also make mental moves without eye movements, by covert shifts of spatial attention. Kosslyn et al. [30] have argued in relation to mental imagery tasks that parietal areas are involved in these shifts of spatial attention. Both in plan–control and plan tasks there was activation in the intraparietal cortex.

4.3. Path to goal

The plan tasks, but not the plan–control, tasks required the subjects to construct and evaluate a path

from the starting array to the specific goal array [13]. Thus, the particular goal had to be represented, the difference noted between the start and goal array, and the moves evaluated as steps towards that goal. We identified the corresponding activations by a conjunction analysis of [PLAN–MOVE vs. PLAN–CONTROL–MOVE] and [PLAN–IMAGINE vs. PLAN–CONTROL–IMAGINE] (analysis 3).

There was no additional activity in the prefrontal cortex for the plan tasks, over and above that seen for the generation and selection of moves, the making of mental moves and the working memory of moves (plan–control tasks). It could be argued that there might have been a small additional activation in prefrontal cortex for the plan vs plan–control conditions, but that PET is not sufficiently sensitive to detect such a difference. However, inspection of the data for the left dorsal prefrontal cortex gives no indication of such a difference (Fig. 3).

There was extensive activation in the prestriate and inferotemporal cortex, extending along the lingual and fusiform gyri. Activation of the ventral prestriate and inferior temporal cortex has been found previously in studies of imagination of objects, pictures or maps when these are manipulated in mind. Kosslyn et al. [29,30] proposed that the generation and use of visual images depends on a neural system that includes a visual buffer in prestriate cortex and a subsystem for encoding object properties and matching them to stored visual memories in the inferior temporal gyri. Johnsrude et al. [21] found activation in the posterior inferotemporal cortex when subjects mentally reoriented a remembered spatial array. The goal pattern in the TOL, or the representation of the difference between the starting position and the goal position, may be regarded as a visual mental representation or 'pattern'. This is also true for the representation of the difference between the goal and a sub-goal on the path to the goal.

When comparing plan with no plan conditions there were small regions of activation posteriorly in the intraparietal sulcus or neighbouring superior parietal cortex. Kosslyn [30] proposed that this cortex was involved in attentional shifts during mental imagery tasks. On the plan tasks the subjects had to evaluate the current position and move. This could be performed by shifting attention between the current state after a proposed move and the representation of the goal in memory. Our study does not allow us to test this hypothesis further.

Finally, in the comparison of plan with plan–control conditions we observed activation of the dorsal premotor cortex, cerebellar nuclei and right cerebellar hemisphere. Both the dorsal premotor cortex [48] and the cerebellar hemisphere [26] are activated when subjects represent movements in their imagination. Kim et al. [27] also reported activation in the dentate nucleus when subjects planned moves.

It is not clear why there was more activation in these areas in the plan than plan–control conditions. The design of our conditions matched the plan–control tasks to the plan tasks in terms of the total time per trial and for the actual moves made. The behavioural data however indicated that they were also equal in the initial thinking time. Despite this close matching, the subjects may have made more mental moves on plan tasks, because some moves would have been selected, mentally made, and then rejected if they did not contribute towards the goal. If additional generation and mental movements were occurring, but the initial thinking time was matched, then the processes of generation and mental moves must have occurred at a higher rate in the plan conditions. Activations of the cerebellum, parietal and premotor cortex during finger movements have been shown to be rate related [19], and this could explain the persisting cerebellar, parietal and premotor activations in analysis 3 (plan vs. plan–control). However, Jenkins et al. [19] also found that there was no relation between the rate at which subjects freely selected moves and the activation of the dorsal prefrontal cortex, and this may explain the lack of residual activation in the dorsal prefrontal cortex.

4.4. Conjunction analysis

The advantage of using conjunction analysis is that it isolates regions that are common to planning, irrespective of whether the subjects did or did not execute the moves. This means that it is not sensitive to differences that occur for one task comparison [45]. The number of moves made in PLAN–MOVE was slightly greater than in PLAN–CONTROL–MOVE (4.07 vs. 4.0 moves per problem) because of errors made on the plan task, but activations relating to this small difference will not survive the conjunction analysis. Similarly we used REST as one baseline for the IMAGINE tasks because we wanted to be able to repeat one of the conditions used in previous studies [2,39]. For the comparison [PLAN–IMAGINE vs. REST] the conditions differ by one move per trial, but the conjunction of [PLAN–MOVE vs. VMC] and [PLAN–IMAGINE vs. REST] (analysis 1) is not sensitive to this difference.

4.5. Clinical implications

The processes of generation and selection of moves, mentally making moves and memory for moves have been shown to activate a common cortical network including dorsal prefrontal, anterior cingulate, premotor and intraparietal cortex. The processes of representing goals and comparing moves with the goal have been shown to activate the intraparietal, prestriate and fusiform cortex.

These results help to explain why patients with frontal lobe lesions are impaired on the TOL. This may not be because the patients cannot represent the goal or evaluate moves as steps on the path towards the goal. The prefrontal cortex is activated by the generation and selection of moves, by mental moves and the memory for moves. Patients with frontal lobe lesions may be impaired on one or more of these processes.

For example, they may be poor at generating moves. Such an impairment would be analogous to the impairment of patients with prefrontal lesions on tests of verbal and design fluency. They generate fewer items than control subjects on these fluency tasks [18,20,22].

Secondly the patients may act before they have selected and mentally made all the moves. Johns [20] examined 20 patients with neurosurgical frontal lesions on the TOL. The problems ranged in difficulty from two to seven moves. The patients solved fewer problems in the minimum number of moves, and this was the case irrespective of the difficulty of the problem. Although the initial thinking time increased with problem difficulty, the patients with right sided lesions took less time to make a first move. This impulsive behaviour, with patients acting without knowing the whole solution, suggests that they may not have mentally made the moves before acting.

Thirdly, the patients may fail to remember all the moves they have planned. Frontal patients have been shown to be impaired on spatial working memory tasks [40]. Morris et al. [34] demonstrated that patients with right frontal lesions were impaired at remembering specified moves in the Tower of Hanoi. This is consistent with our finding that the dorsal prefrontal cortex is activated as much in the plan–control conditions (requiring working memory for moves) as in the plan conditions.

There may be other reasons for the impairment of patients with prefrontal lesions on planning tasks. Morris et al. [33] suggested that poor performance on the Tower of Hanoi task was due to impaired response inhibition in novel situations. The patients were impaired on the first four four-move problems that contained goal-subgoal conflicts, but not on four subsequent five-move problems. The authors proposed that performance on the new counterintuitive moves required inhibition of prepotent moves and that the apparent deficit in 'planning' was due to an inability to deal with novelty in relation to goal-subgoal conflict. As problems with counterintuitive moves became familiar, the importance of response inhibition diminished. However, the patients with bilateral and right prefrontal lesions studied by Johns [20] were impaired on four-move problems when these were spread over 20 trials varying in difficulty from two- to seven-move problems. The patients were no more error prone than controls on the most difficult problems, regardless of when they were presented. While novel counterintuitive moves may be particularly problematic for patients, in our study there was activation of the left prefrontal cortex even after many four-move problems.

Johns [20] also reported that patients with orbitofrontal lesions as the result of closed head injury sometimes attempted illegal moves, suggesting poor response inhibition. The orbitofrontal cortex was activated in a PET study of the TOL by Elliott et al. [8] when planning was compared with a condition in which the subjects simply guessed the number of moves to be made. We also found orbitofrontal activations when the plan tasks (analysis 1) and plan–control tasks (analysis 2) were compared with baseline. Others have shown that the orbital or inferior frontal cortex is activated under conditions that require the inhibition of responses [23,28,36].

5. Conclusion

Our findings suggest that the activation of the prefrontal cortex on the TOL may be due to the generation, selection and memory for moves. Prefrontal activation during planning was not attributable to the 'goal-directed exploration' of alternative moves [4] or the evaluation of a path towards a specified goal.

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