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Journal of Physiology - Paris 99 (2006) 308–317
Journal of Physiology Paris
www.elsevier.com/locate/jphysparis

Planning and problem solving: From neuropsychology to functional neuroimaging

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Abstract

This article provides an overview of recent research on human planning and problem solving. As an introduction, these two cognitive domains will be described and discussed from the perspective of experimental and cognitive psychology. The following sections will focus on the role of the prefrontal cortex in planning and problem solving and on disorders of these functions in patients with frontal-lobe lesions. Specific emphasis will be placed on the Tower of London task, a well established and widely used neuropsychological test of planning ability. We will present an overview of recent behavioural and neuroimaging studies that have employed the Tower of London task to draw specific conclusions about the likely neural and cognitive basis of planning function. Finally, we turn to a number of new directions and recent studies exploring different aspects of planning and problem solving and their association to related cognitive dimensions.

Keywords: Planning; Dorsolateral frontal cortex; Tower of London; Working memory; Executive function

1. Planning and problem solving: evidence from cognitive psychology

In everyday life, the terms "problem solving" and "planning" are often used to describe our efforts to cope with rare or extreme situations requiring very unusual skills or strategies. In contrast, cognitive psychologists define these terms in a very broad sense, as part of our everyday control of actions. "Being confronted with a problem" simply means that we want to achieve a certain goal, whereas the steps to solve this problem are uncertain, unknown, or need to be performed in a particular order. Situations requiring problem solving have thus in common that they require us to take some precautions in order to meet our goals.

Given this cognitive definition of planning and problem solving, what are the basic requirements for successful planning? First, one needs to create a mental representation of both the current situation and the goal. Furthermore, these representations have to be linked by establishing which actions are needed to transform the current state into the goal state. Problems therefore have three general characteristics: (1) an initial state, or the state in which the problem solver sorts out the givens; (2) a goal state, or the solution state that the problem solver tries to achieve; and (3) the steps that the problem solver takes to transform the initial state into the goal state that initially may not be obvious (Sternberg and Ben-Zeev, 2001).

In a similar manner, Anderson (2000) has described three essential features of problem solving (1) goal directedness (the behaviour is clearly organized towards a goal); (2) sub-goal decomposition (the original goal is divided into sub-tasks or sub-goals); (3) operator application. (The term operator refers to an action that transforms one problem state into another problem state. The solution of the overall problem is a sequence of these known operators.)

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doi:10.1016/j.jphysparis.2006.03.014

Problems differ in whether there is one single solution or whether there are many possible ways to achieve the goal. However, all problems require that we choose our actions from a variety of possible steps. That is because (1) there is invariably more than one possible step and (2) some steps are more appropriate than others. A helpful concept for describing the complexity of a particular problem is the so-called "problem space". It integrates all the possible states of a given problem in one (often graphic) representation, with each state being a snapshot of an actual problem situation. Each state can be transformed into another by using the available operators. Thus, there are as many states as can be produced by the application of operators. At the beginning, the problem solver is referred to the initial state and steps on the way to the goal are defined as intermediate states. Finally, the goal itself represents the goal state. As mentioned above, the problem space consists of all possible states. In cognitive science, this is often called the "objective" problem space. Given this complete representation, solving a problem can be reduced to reading the correct path from your mapping of all possible states. However, in reality the state space perceived by a person in a particular problem situation will usually be far from complete. This idea is best represented by the concept of the "subjective" problem space. The search through the problem space requires a person to apply operators, add new states, and evaluate the effectiveness of the operators. All this is performed within one's own representation of the problem. The total of the perceived states and operators comprise the subjective problem space. For example, in finding a way out of a maze, it is usually not possible to simply "read" the right way from an objective problem state, e.g., a map. Moves have to be actively constructed by considering appropriate actions and their consequences. This depends on an adequate representation of the problem, as conceived in the subjective problem space.

There are two fundamental ways of solving a problem: by algorithms or by heuristics. The main characteristic of algorithms is that they provide a safe way to find a solution; they are exhaustive search methods relying on the objective state space, and they therefore always lead to the goal. A basic algorithm consists of examining all possible methods, which ensures a solution, but may be inefficient and unsophisticated. Algorithms are thus often used by computer programs, which have the capacity to process all possible solutions.

However, humans are often not able to solve a problem by searching all the possibilities given constraints on processing resources, e.g., working memory capacity. In contrast to algorithms, the heuristic method is a rule of thumb that provides a powerful tool. Instead of the permutation of all possible moves, heuristics involve a selective search of particular portions of the problem space, namely those that are most likely to produce a solution. The price, however, is that heuristics can be misleading; they cannot ensure that a valid solution is always found. Even if a certain heuristic yields correct results in 99% of all cases, there will always be the possibility of a false outcome.

The difference-reduction heuristic method relies on the problem solver trying to reduce the difference between the current state and the goal state. According to this rule, one chooses the one move that minimises the difference between the current state and the goal by the greatest amount. For this reason, this method is often called "hill climbing", since the problem solver is taking a step higher towards the "peak" or solution. However, hill climbing is sometimes problematic, particularly when in order to reach the correct solution a backward step is required that seems to move the problem solver further from the goal state. For example, in the Tower of London task, it is sometimes necessary to move a ball away from its final position in order to achieve the goal state in the minimum number of moves. Thus, difference reduction is not guaranteed to work, since it provides a rather short-sighted method of how to choose each step with no regard for super-ordinate goals. In short, difference reduction may be useful in some cases, but it can also mislead the problem solver, particularly when the solution requires a higher look-ahead capacity than provided by a simple step-by-step mechanism.

In contrast, the means-ends heuristic method provides a more global perspective on problem solving and is a more sophisticated method of operator selection (Newell and Simon, 1972). This method includes the following steps: first, one has to determine what the goal state is; then the distance between the current problem-solving state and the desired goal state has to be assessed; finally, an operator for reducing the greatest difference between these states is chosen. In contrast to the difference-reduction method, when an operator is applied and an unforeseen obstacle occurs, the problem solver sets the new sub-goal of the removal of the obstacle, the so-called sub-goaling process. Until solved, the sub-goal becomes the highest-priority goal, and it is tackled by again taking the three steps of means-ends analysis just described. Thus, sub-goaling is a recursive procedure that repeats itself until a goal is reached. After all the sub-goals are attained, the final goal is met (Sternberg and Ben-Zeev, 2001).

2. Planning and problem solving: evidence from neuropsychology

The prefrontal cortex has long been thought to play an important role in planning behaviour. The frontal lobes comprise more than 30% of the entire complement of cortical cells and are the part of the cortex that is more highly developed in humans than in other primates. The prefrontal cortex can be thought of in terms of three broad subdivisions: the medial part, the dorsolateral part, and the orbitofrontal region (Karnath and Kammer, 2003). The prefrontal cortex receives input projections from other neocortical areas, especially from parietal and inferotemporal regions. Most of these connections are topographical and reciprocal. The prefrontal cortex also receives information from the hippocampus, the cingulate cortex, the substantia nigra and the thalamus, primarily from the medial dorsal nuclei. The prefrontal cortex sends back projections to the medial dorsal nuclei as well as to the amygdala, the septal nuclei, the basal-ganglia, and the hypothalamus (Thier, 2003). The prefrontal cortex is therefore highly interconnected with other cortical and sub-cortical structures. It is perhaps unsurprising then that this region has been credited with highly complex and multifaceted functions.

Harlow (1868) was the first to argue that frontal-lobe lesions in humans result in a loss of "planning skill", whilst much later, Bianchi (1922), described a loss in the ability to "coordinate the different elements of a complex activity" in monkeys with large frontal lesions. More contemporary accounts have characterised the role of the frontal cortex in planning behaviour using various, similarly descriptive, terms; e.g., "as a general system for sequencing or guiding behaviour towards the attainment of an immediate or distant goal" (Jouandet and Gazzaniga, 1979), or as crucial for the "planning of future actions" (for review, see Shallice, 1988). Until recently, however, the assumed relationship between cognitive planning and the frontal lobes lacked solid empirical support, and was based largely on anecdotal reports of disorganized behaviour in patients with relatively non-specific brain injury, or on the behaviour of monkeys with large excisions of the frontal cortex. Moreover, planning difficulties are not unique to patients with circumscribed frontal-lobe damage. For example, "frontal-like" planning deficits have been described in patients with mild Parkinson's disease and other basal-ganglia disorders, suggesting that equivalence between the prefrontal cortex and planning function cannot be assumed (Morris et al., 1988; Owen et al., 1992, 1995a, 1998).

In 1935, Wilder Penfield and Joseph Evans, neurosurgeons at the Montreal Neurological Institute, described three cases of patients who had sustained extensive neurosurgical excisions of the frontal lobes (Penfield and Evans, 1935). Of particular interest was one young woman who, following surgery, exhibited a marked failure to organize and plan her daily activities. For example, she was unable to plan and prepare an entire family meal, but was nevertheless perfectly capable of cooking the individual dishes. Subsequently, such disabilities have usually been accounted for in terms of deficits in the cognitive processes involved in planning, although rather few studies have addressed this issue directly. An early investigation by Porteus and Kepner (1944) established that, following prefrontal leucotomy, patients were impaired at maze learning, a deficit attributed to a loss of "planning skill". A more direct approach was taken by Klosowska (1976), who developed a novel task that specifically required the development of a plan for successful performance. Subjects were shown a number of objects on a table and were given a specific goal (to cork a bottle). This goal could only be attained by combining a number of discrete steps into a comprehensive plan of action, and then executing each step in the correct order. Fifty patients with unilateral or bilateral frontal-lobe damage of mixed aetiology exhibited a marked deficit on the task relative to a group of 25 patients with more posterior lesions. In addition, many of the frontal-lobe patients reported difficulties with planning and structuring their everyday activities.

Whilst the tasks developed by Klosowska (1976), and earlier by Porteus and Kepner (1944), certainly appear to require cognitive planning, they also have strong visuo-spatial requirements which may have independently contributed to the deficits described. To overcome this difficulty, Shallice and McCarthy (described in Shallice, 1982), developed the "Tower of London" test, a series of problems thought to depend more heavily on planning than on spatial processing abilities. Shallice developed an alternative to the classic Tower of Hanoi task, which he, being a native of England, called the "Tower of London". In comparison with the original version, his test allowed him to produce graded difficulty levels and a greater variety of qualitatively different problems (Shallice, 1982; Shallice and Burgess, 1991). Subjects are required to move coloured beads between three vertical rods of different lengths in order to match a goal arrangement displayed on three similar rods (see Fig. 1). The difficulty of the problem can be manipulated by varying the starting position of the initial arrangement with respect to the goal arrangement.

The Tower of London task clearly requires "forward thinking", or planning, since an early incorrect move can render the problem virtually unsolvable, as all previous steps will have to be retraced and reversed in order to correct the inappropriate move. Thus, the "objective problem space" for the Tower of London test consists of states, which are the configuration of the pegs on the beads, and operators, which consist of moving of a bead from one peg to another. Each problem is composed of two states, that is the "initial state" and the "goal state". Moreover, a "path constraint" is formulated in terms of rules that the problem solver has to take into account for every single move: a ball may only be moved if no other ball is on top of it; only three balls can be placed on the longest stick, two balls on the middle, and one ball on the shortest stick. Accordingly, successful performance typically involves a number of steps via means-end analysis. First, the overall

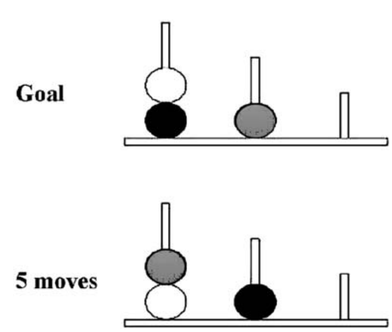

Fig. 1. An example of a five move Tower of London problem. Participants are instructed to plan in their head the moves they have to make before they execute the movements by the computer-mouse.

situation is considered by assessing the initial and goal states with reference to differences in the positions and overall configuration of the balls, then a series of sub-goals is defined, and a sequence of moves is generated to attain these sub-goals. This sequence is refined and revised according to the results of mental rehearsal and, finally, the correct solution is executed. In a first study, reported in Shallice (1982), patients with left anterior cortical pathology were shown to be impaired in the number of moves required to complete the Tower of London problems. This finding could not be explained in terms of visuo-spatial factors, since the results were unchanged when performance was corrected on an individual level for performance on the spatially demanding Block Design sub-test of the Wechsler Adult Intelligence Scale (WAIS).

Owen et al. (1990) assessed performance on this task in 26 neurosurgical patients with unilateral or bilateral frontal-lobe excisions, and later (Owen et al., 1995b), in a group of 20 patients with unilateral temporal-lobe excisions and a group of 11 patients in whom the more selective, amygdalo-hippocampectomy had been performed. Compared to controls matched for age and IQ, the frontal-lobe group required more moves to complete the problems and produced fewer perfect solutions. Initial "thinking", or "*planning*" time was unimpaired in these patients, although the amount of time spent thinking on line (i.e., subsequent to the first move) was significantly prolonged. This pattern of impairment appears to be relatively specific at the cortical level, since no deficits were observed in the two groups of neurosurgical patients with damage to the medial temporal-lobe region (Owen et al., 1995b).

In a follow-up study (Owen et al., 1995a), the Tower of London task was modified to examine the relationship between thinking (planning) time, problem difficulty and solution accuracy in the group of patients with frontal-lobe excisions. Subjects were required to study each of the original Tower of London problems, and then to decide how many moves would be required to reach an ideal solution (i.e., with the minimum number of moves), *without actually moving any of the balls*. Because this modification required subjects to evaluate and solve the full problems, without executing any of the necessary sub-goal operations (i.e., moving the balls), it was no longer possible to compromise "initial planning time" (i.e., the time before a response was made) in favour of "on-line" consideration of the problem during the execution of the solution (i.e., "subsequent thinking time"). This modification served to encourage subjects to plan the solution in full, before initiating a response. The effects of this alteration were clear-cut with respect to the performance of the control subjects, as compared to the data obtained previously by Owen et al. (1990) using the earlier version of this task: the initial thinking time was (during the more challenging four and five move problems) approximately twice as long as that reported previously (e.g., Owen et al., 1990). In the frontal-lobe patients, the results of the previous study were essentially confirmed; that is, compared to the matched control group, the frontal-lobe patients were significantly impaired in terms of solution accuracy, whilst solution latency (or "initial thinking time"), was relatively preserved. One might have expected to see prolonged thinking times in the frontal-lobe group, given those patients' profound difficulty with solving the problems and their prolonged "subsequent thinking" times on the earlier version of this task (Owen et al., 1990). However, in the previous study, the prolonged *subsequent* thinking time in frontal-lobe patients was assumed to reflect the additional time required to revise and refine a solution following an inadequately planned, or impulsive, attempt to solve the problem. Because the performance on the modified Tower of London task used in the later study was measured by a single response, the results further suggested that the behaviour of frontal-lobe patients in tests that require forward thinking or planning is indeed impulsive; that is, these patients initiate a response, or make the first move, before they have successfully generated an appropriate solution to the problem. This view is consistent with the conclusions of other investigators (e.g., Stuss and Benson, 1984).

Up to now, numerous studies have described the assessment of planning disabilities with the Tower of London task in clinical and in non-clinical populations. Examinations with patient groups primarily examined the deficits after frontal-lobe lesions or frontal-lobe dysfunctions (Carlin et al., 2000; Cockburn, 1995; Levin et al., 1994; Owen et al., 1990, 1995a,b; Shallice, 1982, 1988). It was also shown that patients with schizophrenia (Morris et al., 1995; Morice and Delahunty, 1996; Pantelis et al., 1997; Staal et al., 2000), Huntington's disease (Lange et al., 1995b; Watkins et al., 2000), and Parkinson's disease (Owen et al., 1992; Lange et al., 1995a; Hodgson et al., 2002; Turner et al., 2002) have impaired planning abilities compared to healthy normal participants. In combination, the results of these studies demonstrate a significant association between cognitive planning and the frontal cortex in humans.

3. Planning and problem solving: evidence from functional neuroimaging

In patient studies, it is not possible to determine with anatomical precision the areas of the frontal cortex involved in a given cognitive process, since the excisions are rarely confined to specific cytoarchitectonic areas. In recent years, functional neuroimaging techniques such as single photon emission tomography (SPECT), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI) have provided a unique opportunity for assessing the relationship between patterns of neuronal activation and different aspects of cognitive planning in healthy control volunteers.

Andreasen et al. (1992) performed a SPECT-study of the Tower of London task in order to prove the "hypofrontality hypothesis" in patients suffering from schizophrenia. Healthy normal volunteers who served as control group showed an increase in brain activation bilaterally in the prefrontal cortex during this planning task. Two subsequent SPECT studies of planning in normal subjects also demonstrated increased cerebral blood flow (CBF) in the frontal cortex during versions of the Tower of London task (Morris et al., 1993; Rezai et al., 1993). However, the spatial resolution of SPECT is not sufficient to investigate functional specialisation *within* the human frontal cortex. Thus, Owen et al. (1996) used PET with its better spatial resolution to examine regional CBF while subjects solved either simple or difficult Tower of London problems. Blood flow during these conditions was compared to that during a control condition, which involved identical stimuli and responses but required minimal planning. When activation in the control condition was subtracted from that during the difficult planning condition, a significant regional CBF change was observed in the left mid-dorsolateral frontal cortex. In the human brain, this region comprises mainly cytoarchitectonic Brodmann areas 9 and 46 (Brodmann, 1908), which occupy the mid-part of the superior and middle frontal gyri, with a considerable proportion of this cortex lying within the depths of the middle frontal sulcus. Although the change in rCBF was only statistically significant in the left frontal cortex, an area of increased blood flow which just failed to reach significance by standard criteria was observed in a slightly more anterior location in the opposite hemisphere (see Fig. 2). Similar results were reported in two later studies, which employed the modified ''one-touch'' version of the Tower of London task used by Owen et al., 1995a. Thus, bilateral dorsolateral frontal activation was observed in both cases (Baker et al., 1996).

One significant problem with many of these studies is that the selection of a control task invariably determines, to a large extent, the pattern of activation observed for subtractions. For example, as all cognitive tasks involve some planning at different levels of complexity, the relationship between the experimental (e.g., planning) task and the (frequently inadequately-defined) planning *demands* of the control task can complicate the interpretation of imaging data. In addition, the visuo-motor demands of the experimental (e.g., planning) and control tasks may differ, even in subtle ways, which may be a further challenge during the interpretation of the results. One approach to this problem is to use a parametric or correlational task design, which involves no control task per se, but rather multiple scans with similar planning requirements, but different levels of task difficulty. Dagher et al. (1999) used this approach to examine regional cerebral blood flow with PET during increasingly complex Tower of London problems. Volunteers were scanned while performing Tower of London problems requiring one to five moves, and during a rest condition which involved no task. Activity in the dorsolateral frontal cortex covaried with complexity, while activity in posterior parietal cortex and in the occipital lobe was shown to be independent of complexity (see Fig. 3). This suggests that, while the dorsolateral frontal cortex plays a central role in planning solutions to the Tower of London problems, posterior cortical areas, such as occipital and parietal cortex, make more basic contributions to aspects of visual and spatial processing during the task.

By correlating regional CBF changes with the number of moves made to reach a solution (irrespective of the minimum number of moves actually required to solve the problem), it was also possible to differentiate between regions involved in planning and those involved in movement execution (see Fig. 4). Within the basal-ganglia, for example, movement-related changes were observed in the putamen, while problem complexity (but movement-independent) changes were observed in the caudate nucleus (see Fig. 4). The latter finding may help to explain why 'frontal-like' Tower of London impairments are often observed in patient groups with basal-ganglia pathology such as Parkinson's disease (e.g., Morris et al., 1988; Owen et al., 1992), and it accords fully with the observation that task performance is accompanied by abnormal regional CBF changes in the basal-ganglia in these groups (e.g., Owen et al., 1998; Dagher et al., 2001; Cools et al., 2002).

Lazeron et al. (2000) adapted the Tower of London task for functional magnetic resonance imaging (fMRI). FMRI is a non-invasive technique that allows the measurement of brain activity indirectly, by means of changes in the blood oxygen level (Ogawa et al., 1990; Kwong et al., 1992). An advantage of this technique compared to other functional brain imaging techniques is its high spatial and temporal resolution. Lazeron et al. (2000) presented two to seven moves problems and made a further division into easy (2–4 moves) and difficult (5–7 moves) configurations, to compare different levels of planning activity. As a control condition, participants simply had to add the number of yellow and blue balls without paying attention to their configuration. The group average images of the active condition (easy and difficult configurations combined) yielded activation on both sides in the frontal and parietal lobes, the cerebellum, and the insula. More specifically, activation of frontal structures was observed bilaterally in the middle frontal gyrus and the adjacent part of the inferior frontal sulcus (with some preference for the right hemisphere), and in the anterior part of the cingulate gyrus. The parietal and occipital regions involved were the precuneus and cuneus as well as the left supramarginal and angular gyrus. These findings are in agreement with grouped data of previous positron emission tomography results. Interestingly, Lazeron et al. did not report significant differences in brain activation when comparing the easy and the difficult planning level. In addition, they did not observe activation in the basal-ganglia. Therefore, a correlational design might have been advantageous to allow the detection of further activations. In addition, a detailed assessment of the performance of the Tower of London task inside the scanner may also provide clearer results than choosing the number of movements between two possibilities, which probably encouraged participants to guess the correct solution. Van den Heuvel et al. (2003) investigated which brain

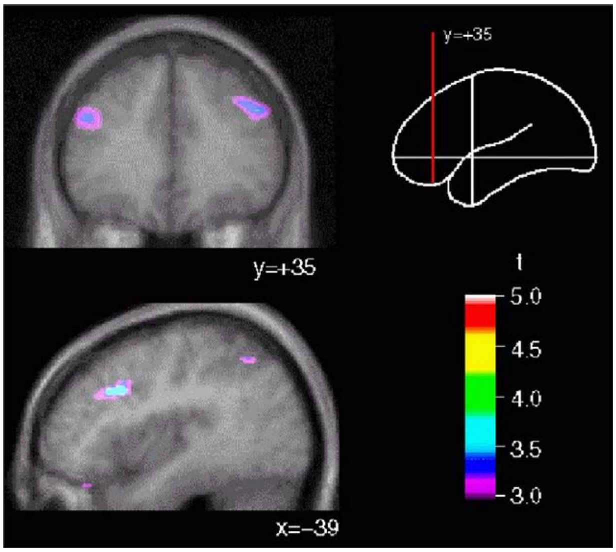

Fig. 2. Activation in the mid-dorsolateral frontal cortex during Tower of London planning (adapted from Owen et al., 1996).

structures are recruited in planning tasks of increasing complexity. For this purpose they designed a parametric event-related functional MRI version of the Tower of London task. Subjects were presented one to five move problems in a pseudo-randomized order in the scanner. Increased task load was correlated with activity in bilateral precuneus, bilateral inferior parietal cortex, bilateral premotor cortex, left supplementary motor area, and bilateral dorsolateral prefrontal cortex. In contrast to Lazeron et al. (2000), Van den Heuvel et al. (2003) report about brain activation in the striatum during planning. Increasing task complexity was associated with activity in the right caudate nucleus and right globus pallidus. Therefore, these findings underline the important role of the frontostriatal system in complex planning.

In summary, recent functional neuroimaging studies have been able to confirm and extend previous investigations in patients by identifying with greater anatomical precision the frontal cortical area that appears critical for

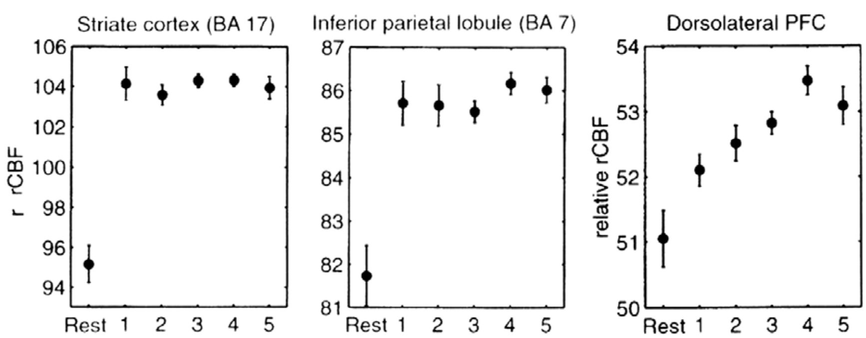

Fig. 3. During planning, activation in the dorsolateral frontal cortex covaries with task complexity while activity in the occipital and parietal lobes is independent of task complexity (adapted from Dagher et al., 1999).

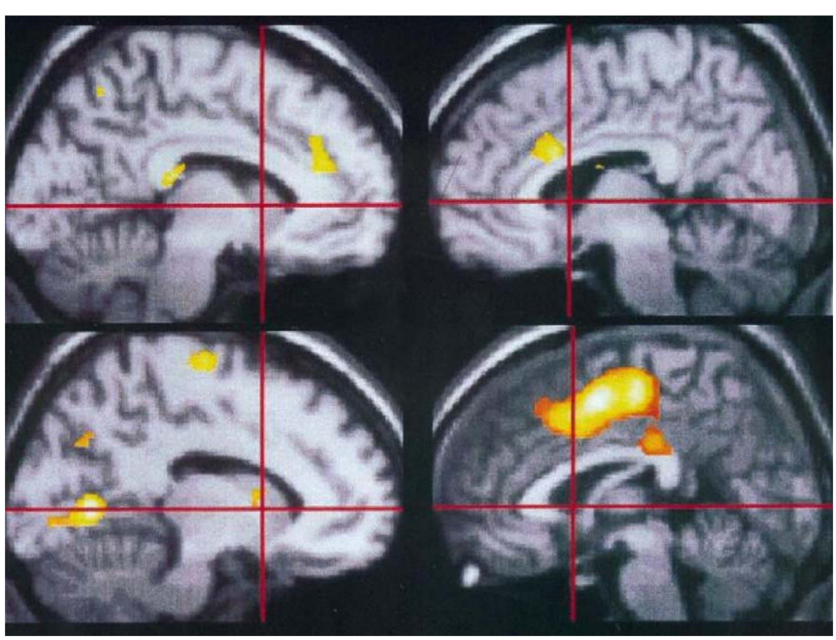

Fig. 4. By correlating regional CBF changes with the number of moves made to reach a solution during the Tower of London task, it is possible to differentiate between regions involved in planning (top row) and those involved in movement execution (bottom row) (adapted from Dagher et al., 1999).

performance on the Tower of London planning task; namely, the mid-dorsolateral frontal region. The combined evidence from different functional neuroimaging studies (e.g., Baker et al., 1996; Dagher et al., 1999; Owen et al., 1996, 1998; Lazeron et al., 2000; Van den Heuvel et al., 2003) and previous investigations in patients (e.g., Owen et al., 1990, 1995a) suggests that, within the dorsolateral frontal region, neither of the two hemispheres plays a dominant role, at least in the type of high-level planning that is required in the Tower of London task. However, one should bear in mind that a number of cortical and sub-cortical regions not located in prefrontal cortex were also activated by the versions of the Tower of London task used by Owen et al. (1996) and/or Dagher et al. (1999), including the caudate nucleus, the presupplementary motor area, the anterior premotor cortex, the posterior parietal cortex, and the cerebellum (Rowe et al., 2001; Van den Heuvel et al., 2003). The available anatomical and functional neuroimaging data suggest, therefore, that whilst the mid-dorsolateral frontal cortex plays a critical role in complex planning behaviour, it does so through close functional interactions with multiple cortical and sub-cortical regions.

4. Planning and problem solving: new directions – where do we go from here?

Some authors have tried to define the cognitive functions necessary to solve the Tower of London task. Carlin et al. (2000) described the cognitive processes involved in the Tower of London task as a "look-ahead mechanism", designed to generate multiple sequences of hypothetical events and their consequences, the development of stored structured event complexes that can guide movement from an initial to a goal state, execution-linked anticipation of future events, and recognition of goal attainment. Dehaene and Changeux (1997) and Changeux and Dehaene (2000) suggest in their hierarchical model a level of programming, the so-called "plan" level. At this level, sequences of operations (plans) must be selected, executed, evaluated, and accepted or withdrawn depending on their ability to bring the problems to a solution. Polk et al. (2002) propose that the generation and maintenance of sub-goal representations is a critical part of problem solving in tasks such as the ToL.

Other authors have tried to find relationships between specific cognitive demands and the Tower of London. Robbins et al. (1998) administered several tests from the CANTAB neuropsychological test battery together with the Tower of London. They showed that the Tower of London loaded either on a factor with spatial working memory and fluid visuo-spatial intelligence, or that the Tower of London performance represented a unique factor when the number of selected tests was increased for the factor analysis. Krikorian et al. (1994) investigated the correlation of Tower of London performance with a verbal test (the Peabody Picture Vocabulary Test – Revised; PPVTR; Dunn and Dunn, 1981) and with the Porteus Maze Test (PMT; Porteus, 1995) as a configural planning measure. Correlations between PPVTR scores and performance on the Tower of London and on the PMT were generally low, and not statistically meaningful. They also showed that the Tower of London scores increased with age (from the first to the eighth grade), suggesting that planning abilities necessitated for the test undergoes development through childhood (see also Andres and Van der Linden, 2000).

In discussions about the cognitive processes involved in the Tower of London, the role of memory is often highlighted (Phillips et al., 1999). For example, Cohen (1996) argues that working memory is important for formulating, retaining, and implementing plans as well as revising them on-line. Based on the three component model of working memory of Baddeley and Hitch (1974) and Baddeley (1986), contrasting assumptions about the modality of working memory for the Tower of London performance exist in the literature. These assertions mostly rely on the proposed sub-division of working memory into a "central executive", responsible for cognitive functions as planning, a "verbal buffer" and a "visuo-spatial buffer" needed for the temporary storage of verbal and visuo-spatial information, respectively.

Since the presentation and response requirements of the Tower of London are visual and spatial, some authors stress the importance of visuo-spatial memory resources (Joyce and Robbins, 1991; Morice and Delahunty, 1996; Owen et al., 1996; Phillips et al., 1999; Robbins et al., 1998; Temple et al., 1996; Welsh et al., 1999). Welsh et al. (1999) report a correlational study of various memory measures and Tower of London performance. They showed that indices of visuo-spatial working memory and inhibition explain more than half of the variance in Tower of London performance. Unfortunately, Welsh et al. did not include verbal memory tasks in their analyses, so that their results allow no conclusions on the specificity of visuo-spatial working memory demand of the Tower of London.

Other authors argue that active verbal rehearsal is involved in the Tower of London, because patient and brain neuroimaging studies in normal adults showed the involvement of the left rather than the right hemisphere in the task (Glosser and Goodglas, 1990; Morris et al., 1993; Shallice, 1982).

In contrast to the assumption that working memory is a basic requirement to solve Tower of London problems, Ward and Allport (1997) describe a study in which working memory resources did not limit performance on the Tower of London task. The memory load of the Tower of London was reduced by allowing on-screen movements of the disks during planning. Decreasing memory load did not affect the time spent planning. However, the effect on the number of excess moves made was not reported in the study. Phillips et al. (2001) even question the nature of planning in the Tower of London, since in their study preplanning did not offer benefits in terms of quicker performance, or more accurate solution. Their results indicate that most participants could only make accurate preplans up to two subgoals ahead.

In order to assess the cognitive processes involved in the Tower of London and to predict the optimal Tower of London performance, Unterrainer et al. (2004) studied the relationship of the Tower of London with other cognitive dimensions. They examined whether visuo-spatial, and/or verbal intelligence/working memory tests as well as fluid intelligence can serve as predictors of Tower of London performance. Data analysis using a stepwise multiple regression yielded only fluid intelligence as significant predictor for the Tower of London performance. In a principal component analysis, the number of correctly solved trials (5–7 moves) on the Tower of London had the highest loading on a unique factor, while none of the other tests loaded on this "planning" component. These results suggest that the Tower of London assesses predominantly planning and problem solving, and cannot sufficiently be explained by other cognitive demands. Gilhooly et al. (2002) recently assessed the relation between verbal and visuo-spatial working memory tasks as well as the Tower of London test. Interestingly, in their study an exploratory factor analysis revealed three factors, with the performance of the Tower of London task loading on a "visuo-spatial" factor. In contrast to Unterrainer et al. (2004), Gilhooly et al. (2002) used the five-disc Tower of London task. Participants were thus exposed to longer planning sequences as in the classical three disc version of Shallice (1982). In addition, the three sticks in Gilhooly's version were of equal length, and therefore demanded less complex planning strategies than the three sticks of variable lengths in the original version. Thus, these two studies can not be compared easily. In the following section, it will be demonstrated that minor differences at the instruction level can already lead to serious differences in the Tower of London performance. Since the original development of the Tower of London in 1982, a broad range of versions were developed that differed from the original version (for review, see Berg and Byrd, 2002). In addition to the original three-rod design, Kafer and Hunter (1997) used a modified version with four beads and four rods. Phillips et al. (1999, 2001) and Ward and Allport (1997) argued that the 3-disc Tower of London, although useful for special populations, is too simple for the investigation of healthy subjects' planning ability. They increased the number of discs to four and five and equalized the rods' length to enable longer move sequences (see also Gilhooly et al., 2002). Other differences arose in the exact instructions given to the subjects. While participants were often instructed to make full mental plans before beginning to execute movements (e.g., Gilhooly et al., 2002; Morris et al., 1993; Owen et al., 1995a; Owen, 1997), no explicit instructions were given in other studies (e.g., Temple et al., 1996).

The possible influence of these differences in instructions were directly examined by Phillips et al. (2001). They compared three different types of instructions: (a) to solve the problems in as few moves as possible; (b) as for instruction a, plus to "plan in your head the moves you have to make to"; (c) as for instruction b, but with the minimum number of moves required to match the goal given at the beginning of each trial. Interestingly, Phillips et al. (2001) did not observe differences in the number of trials solved in minimum moves between the three instruction conditions, although the preplanning time was significantly longer in the conditions b and c as compared to a. However, Ward and Allport (1997) and Unterrainer et al. (2004) found that better performance correlated with longer preplanning time. Phillips et al. (2001) also failed to find differences between the non-cue (minimum number of moves not presented) and cue condition (minimum number of moves Tower of London). This is at odds with introspection, since obviously the cue condition with its hint for effective planning should be easier to solve.

Since Phillips et al. (2001) used a hierarchical study design, they were restricted to comparisons between the three groups. In order to overcome this limitation, Unterrainer et al. (2003) developed an experimental design for two instruction groups which also allowed within-subject comparisons between the two cueing conditions. In addition to effects of instructions and cueing, Unterrainer et al. examined whether previous experience with the planning operations required by the Tower of London also influences task performance. For example, it appears possible that participants learn to solve planning tasks in the course of solving Tower of London problems, and therefore increase their performance in the second part of a test session. Such effects could also interact with test instructions and cueing, e.g., participants may mostly benefit from cues about the minimum number of moves at the beginning of a test session, while they are able to solve the task efficiently without such cues at later stages. For this purpose, an experimental design was set up that allowed the joint examination of the effects of instruction, cueing, and learning as well as their interactions.

The results showed that participants who were instructed to make full mental plans before beginning to execute movements (preplanning condition) solved significantly more problems than people who started immediately with task-related movements (on-line condition). As for the effects of cueing, participants with the minimum number of moves predetermined (cue condition) solved more trials than people who were only instructed to solve the problems in as few moves as possible (non-cue condition). Participants generally increased performance in the second part of the test session. However, an interaction of presentation order of the cueing condition with learning indicated that people who started the tasks with the non-cue version showed significantly better performance in the following cue condition, while participants who started with the cue condition stayed at the same performance level for both versions.

This study clearly demonstrates that different instructions, cueing conditions, and learning effects have a strong impact on Tower of London performance. These findings therefore help to explain divergences in the results of the numerous publications on the Tower of London, and they imply that comparisons between the results of different studies are often compromised by differences in the versions of the test employed (see also Berg and Byrd, 2002). It follows that one standardized version of the Tower of London should be applied in research and clinical practice, or that at least all necessary parameters should be reported. In addition, our study showed that the original Tower of London version by Shallice (1982) offers a variety of problems, which appear suitable for research with both special patient groups and healthy volunteers. The employment of this original version would thus clearly facilitate the comparability of different samples.

5. Conclusions

For future research, statistical analyses like structural equation modelling may help to explain functional interactions between different brain regions involved in planning. In addition, more individual approaches, like the detailed assessment of the Tower of London performance and its relation to brain activity, or an exact examination of the temporal course of this task, should also give useful insights into the neuronal mechanism of cognitive planning. Finally, the application of transcranial magnetic stimulation to prespecified cortical areas known to be important for planning could also yield important insights into the specific function of the underlying neural structures.

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