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Research Report

An fMRI study of the Tower of London: A look at problem structure differences

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ABSTRACT

The aim of the current study was to explore the effects of problem structure, namely goal hierarchy and number of optimal solution paths, on the neural architecture that supports problem-solving and planning. Here, six-move problems with both an unambiguous and ambiguous goal hierarchy and single and multiple optimal solution paths were examined. In the task used, participants were encouraged to generate a solution plan before execution. The behavioral results revealed that problem-solving time and accuracy were both affected by both problem parameters. The fMRI activation results revealed three major findings. First, the right prefrontal cortex revealed a significantly different activation pattern than the other regions examined. This was the only region that revealed a larger response during the execution phase than the planning phase. Second, the effect of goal hierarchy was strongest during the execution phase. Finally, while there was no main effect of number of optimal solution paths, this parameter interacted with goal hierarchy in a number of regions across the brain. The present study also suggests that the minimum number of moves may not be the best measure of problem difficulty and that greater care be taken in the selection of TOL problems for both experimental studies as well as clinical assessment.

1. Introduction

The TOL has been used extensively to study planning processes (Baker et al., 1996; Berg and Byrd, 2002; Carder et al., 2004; Dagher et al., 1999; Newman et al., 2003; Newman and Pittman, 2007; Unterrainer et al., 2003, 2004). However, one problem with the use of the TOL to study planning is that typically problem difficulty is manipulated by varying the minimum number of moves. However, when comparing "easy" problems with a few moves, say 2 moves, with "difficult" problems with many moves, say 6 moves, much more than planning processes are affected. Working memory, visuo-spatial and motor processes are also affected by increasing the minimum number of moves.

Recent studies examining problem structure in the TOL have found parameters such as goal hierarchy (Kaller et al., 2004; Newman and Pittman, 2007; McKinlay et al., 2008), number of optimal solution paths (Newman and Pittman, 2007) and search depth (McKinlay et al., 2008) significantly affected planning performance. For example, in a study examining Parkinson's disease patients' TOL performance, search depth (the number of subgoal moves before the first ball is placed in its goal position) and goal hierarchy (the ambiguity of goal priorities) were manipulated and performance was found to be affected by both parameters (McKinlay et al., 2008).

In the current study both goal hierarchy and number of optimal solution paths were manipulated. Goal hierarchy con-

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cerns the ambiguity of goal priorities. Ambiguity is manipulated by varying the arrangement of the goal state. As shown in Fig. 1 (top), problems with an unambiguous goal hierarchy have tower goal states. The problems are unambiguous because the first goal is clear; the first goal is to place the ball located in the deepest position in bin one in the goal state (e.g., in Fig. 1 (top) put the red ball in its goal position first). There are two types of ambiguous problems, completely ambiguous (the goal state has a ball in each of the 3 bins) and partially ambiguous. In both types of ambiguous problems the first goal is not clear. In Fig. 1 (bottom), for example, it is not at all obvious without some scrutiny, which ball, the red, blue or yellow ball, to place in its goal position first.

The primary aim of the current study was to explore the underlying neural network that supports TOL problem-solving. To accomplish this aim we manipulated two problem structure parameters: goal hierarchy and number of optimal solution paths in problems with the same minimum number of moves. Functional magnetic resonance imaging (fMRI) was performed while well trained participants solved six-move TOL problems. The neural network that has been implicated in the TOL includes regions that have been associated with visuo-spatial processing (parietal cortex), and executive processing such as working memory (prefrontal regions), planning (prefrontal cortex and the basal ganglia) and error detection (anterior cingulate) [Baker et al., 1996; Beauchamp et al., 2003; Dagher et al., 1999; Newman et al., 2003; Wagner et al., 2006]. Based on previous studies examining the effect of goal hierarchy we expected ambiguous problems to be more demanding in terms of planning processes. As a result, we expected to observe greater activation in prefrontal and parietal regions for the ambiguous compared to the unambi-

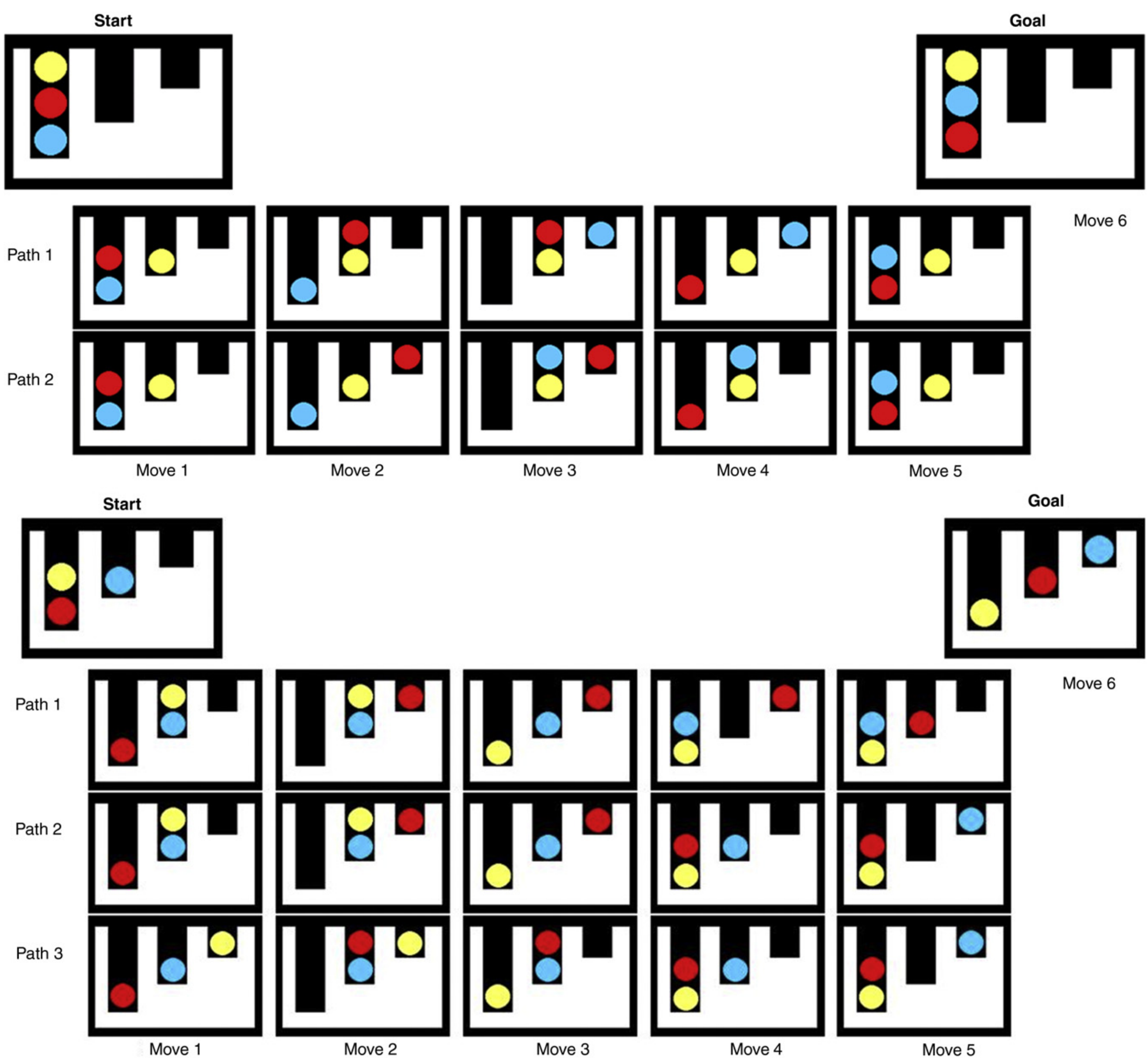

Fig. 1 – Example multi-path problems. The top figure depicts an unambiguous multi-path problem with each of the possible solution paths. The bottom figure depicts an ambiguous, multi-path problem.