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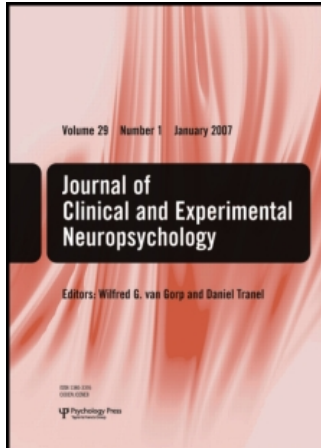
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The Tower of London: A study of the effect of problem structure on planning

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Only recently has there been any consideration of the influence of the problem structure on Tower of London task (TOL) performance. Not surprisingly, these few studies that have investigated this issue have found significant differences in the cognitive demands of individual TOL problems. Based on these previous findings, the aim of the current study was to further explore the effects of two problem characteristics on the planning process—namely, goal hierarchy and the number of optimal solution paths. A number of performance measures when solving six-move problems were examined, including preplanning time, movement time, and accuracy. Analysis of the preplanning time revealed that it was significantly affected by goal hierarchy but not the number of solution paths. The individual movement times, however, revealed effects for both goal hierarchy and the number of optimal solution paths. The number of paths only affected movement times at specific moves: those corresponding to the initiation of a subgoal chunk. The results are discussed in terms of the influence of preplanning on subsequent performance. The present study also suggests that greater care be taken in the selection of TOL problems.

INTRODUCTION

The ability to plan and schedule one's actions is an essential part of a functional life. Yet we still do not have a clear characterization of the underlying cognitive processes or the neural architecture that support it. Generally speaking, planning involves charting a course between two states. This charting takes place not in the real world but in a "modeling space" where the consequences of actions can be observed (Goel, Grafman, Tajik, Gana, & Danto, 1997). One task that has been used extensively to assess planning function is the Tower of London task (TOL) developed by Shallice (1982). Since its development there have been a number of TOL variants studied.

Several studies have found that certain clinical populations, particularly frontal lobe patients, show poor performance on the TOL, and this result has been taken as evidence that the frontal cortex is involved in planning processes (Shallice, 1982; Shallice & Burgess, 1991; Morris, Ahmed, Syed, & Toone, 1993; Owen, Downes, Sahakian,

Polkey, & Robbins, 1990). In fact, the use of the TOL has become incredibly widespread, with it being used to examine a number of clinical disorders including Parkinson's (Morris et al., 1988), Huntington's (Lawrence et al., 1998), and autism (Hughes, Plume, & Leboyer, 1999). In addition, the task has been used to study normal populations with the use of both behavioral (Humes, Welsh, Retslaff, & Cookson, 1997; Owen et al., 1990; Phillips, Wynn, Gilhooly, Della Sala, & Logie, 1999; Phillips, Wynn, McPherson, & Gilhooly, 2001; Shallice, 1982; Unterrainer, Rahm, Halsband, & Kaller, 2005; Ward & Allport, 1997) and neuroimaging (Baker et al., 1996; Dagher, Owen, Boecker, & Brooks, 1999; Newman, Carpenter, Varma, & Just, 2003) studies. However, it has only been recently that investigators have considered the influence of the problem structure of the TOL problem on subsequent planning processes (Carder, Handley, & Perfect, 2004; Kaller, Unterrainer, Rahm, & Halsband, 2004; Unterrainer et al., 2005; Ward & Allport, 1997). Not surprisingly, these studies have found that

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there can be significant differences in the cognitive demands of individual TOL problems (Humes et al., 1997; Kafer & Hunter, 1997; Kaller et al., 2004). Based on these previous findings, the aim of the current study is to further explore the effects of two problem characteristics on planning. More specifically, the present study was designed to assess the influence of two parameters—goal hierarchy and number of optimal solution paths—on TOL performance.

Here problem structure was manipulated by using a parameter used previously by Kaller and colleagues (2004): goal hierarchy. Goal hierarchy concerns the ambiguity of goal priorities. This

ambiguity is manipulated by varying the arrangement of the goal state. As shown in Figure 1A, 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 1 in the goal state (e.g., in Figure 1A 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 three bins) and partially ambiguous. In both types of ambiguous problems the first goal is not clear. In Figure 1B, for example, it is not at all obvious which ball—the red, blue, or yellow ball—to place

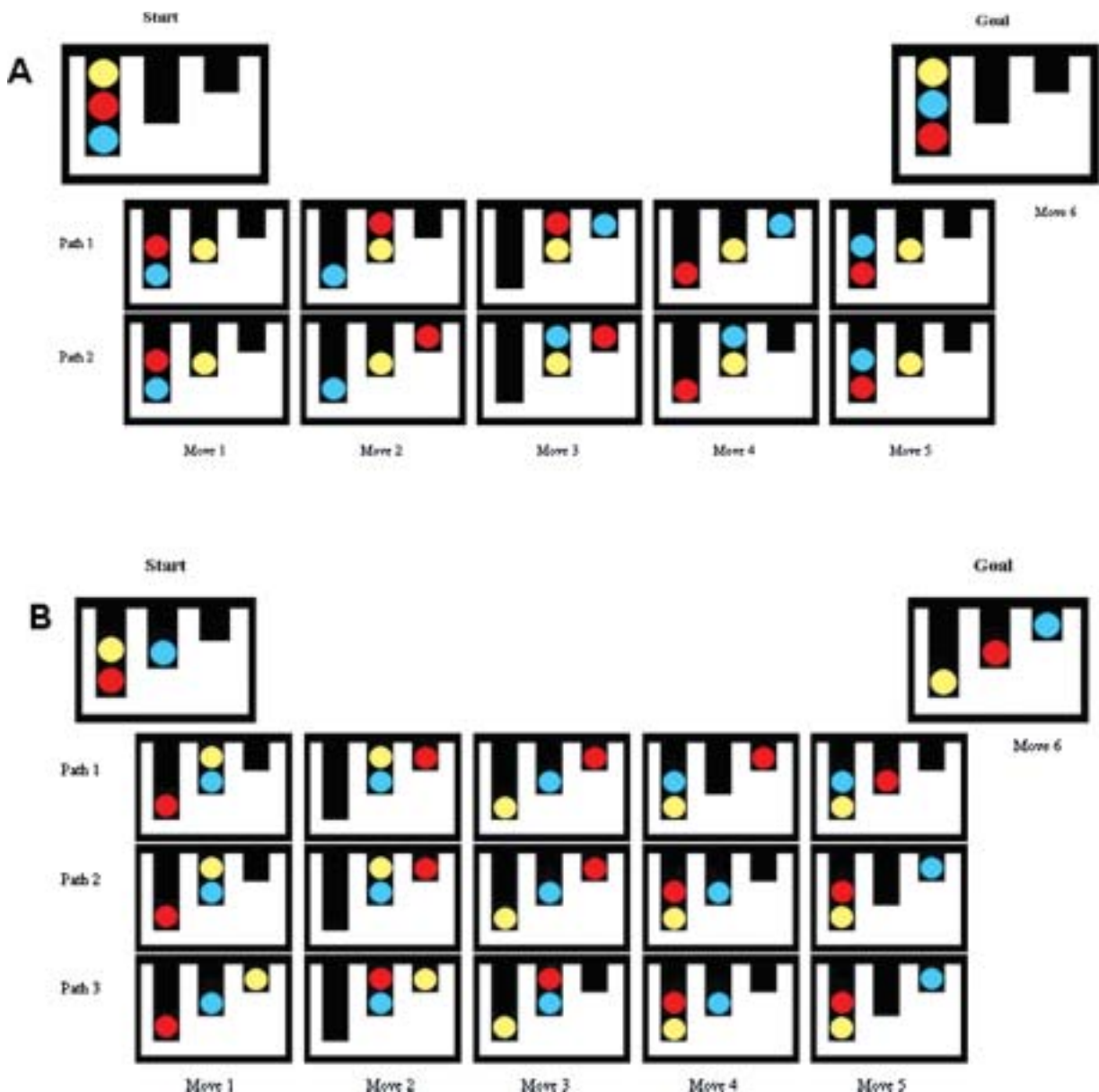


Figure 1. Example multipath problems. A: an unambiguous multipath problem with each of the possible solution paths. B: an ambiguous multipath problem.

in its goal position first. Goal hierarchy has been found in previous studies to strongly affect planning in both adults (Kaller et al., 2004; Ward & Allport, 1997) and children (Klahr, 1985; Klahr & Robinson, 1981).

In addition to manipulating goal hierarchy, the number of optimal solution paths was also varied. Most of the problems we face in real life, including scientific, social, political, and economic, are ill-structured (Sinnott, 1989; Voss, Wolfe, Lawrence, & Engle, 1991) while most experimental studies examine well-structured problems, like the TOL. Well-structured problems have a clear start and goal state with a limited number of paths to the goal. Ill-structured problems, on the other hand, do not have a clearly defined goal state and tend to have a large number of paths to the goal. By presenting TOL problems in which the number of moves is held constant while varying the number of paths to the solution, one of the dimensions outlined by Goel (1995) that define ill-structured problems—namely the constraints on the solution path—is manipulated. Even though increasing the number of optimal solution paths in a well-structured problem does not transform it into an ill-structured problem, it may allow for greater insight into one dimension of ill-structured problem solving. In the current study, single-path problems were compared to multipath problems. However, in the present study the aim was to examine the effect of number of paths on planning and execution processes, as well as how it may interfere with setting goal priorities.

METHOD

Participants

A total of 24 undergraduates from the Indiana University community participated in the experiment (age $M = 19.8$ years, $SD = 3.4$). The sample was composed of 10 men and 14 women; all were right-handed. Participants were all introductory psychology students and gave informed consent to participate.

Procedure

In the computerized TOL paradigm used in the current study, participants were presented with two configurations (a start state and a goal state) of three colored balls arranged in three bins. The start (current) state was presented in the center of the screen while the goal state was displayed in the top right corner of the screen. Participants

were told to transform the start state into the goal state in the minimum number of moves; they were not informed of the minimum number of moves. They moved the balls by first clicking on the ball that they wanted to move and then its destination with a computer mouse. Constraints on the possible moves are determined by the different depths of the bins (the three bins hold three balls, two balls, and one ball, respectively) and being able to move only the top-most balls to a different bin.

While both six- and five-move problems were presented, only six-move problems were examined in the current study. A two-factor design was employed; as such the problems were one of four types. The two factors examined were number of optimal solution paths (1 versus 2/3) and goal hierarchy (unambiguous versus ambiguous). Because of the structure of the TOL variant used, the number of optimal solution paths varied with goal hierarchy such that unambiguous, multipath problems had two optimal solution paths while ambiguous, multipath problems had three optimal solution paths. The problems used are listed in Table 1 using the Berg and Byrd (2002) nomenclature.

Each of the four conditions consisted of 12 trials. In order to ensure that the trials within each condition were indeed similar, a one-factor analysis of variance (ANOVA) examining the movement times across trials in each condition revealed that there were no differences between trials within a condition (all p -values were greater than .25). Participants were given the following instructions: "Try to solve the problems in the minimum number of moves by planning ahead. The goal is to solve the problem as quickly and accurately as possible, but do plan ahead before moving any balls to ensure that you use the most efficient route. Some of the problems have multiple solutions. Please try to consider all solution paths and use the most efficient (the one with the fewest number of moves) solution." Therefore participants were to generate a plan to move the balls from the start configuration to match the goal configuration and to only start moving the balls after a plan was generated. Thus, this TOL task required participants to "look ahead" and map out a plan to solve the problem prior to execution.

The following measures were recorded for analysis: number of correctly solved trials, the number of extra moves made during incorrectly solved trials, total solution time, and movement times. Because all of the trials were solved (although not all in the minimum number of moves), the number of extra moves that the participants made was used

TABLE 1
Problem set

	Single path		Multipath	
	Start state	Goal state	Start state	Goal state
Unambiguous	36	31	62	11
	53	11	12	61
	32	11	41	51
	33	51	61	11
	62	21	36	41
	43	21	32	21
	12	51	11	61
	13	31	31	21
	22	41	21	31
	23	61	22	31
	42	61	42	51
	63	41	51	41
	Ambiguous	36	25	14
66		45	13	55
16		35	53	35
26		54	43	65
52		64	44	25
22		43	34	55
11		53	63	25
12		53	24	65
21		43	33	15
61		23	23	45
42		15	64	45
51		33	54	15

Note. The numbers correspond to the Berg and Byrd (2002) notation.

as an indication of accuracy. Total solution time is defined as the time from stimulus onset to problem completion. Movement time is defined as the time to select a ball to move plus the time to select a destination. Preplanning time was defined as the time between problem presentation onset and the first move, or the movement time associated with Move 1.

RESULTS

Accuracy

An ANOVA with number of optimal solution paths and goal hierarchy as within-subject factors revealed that the number of trials solved in the minimum number of moves was significantly influenced by goal hierarchy and number of solution paths (see Figure 2A). The multipath problems elicited a larger number of correct solutions than did the single-path problems, $F(1, 23) = 56.65, p < .0001$. The unambiguous problems also elicited a larger number of correctly solved problems, $F(1, 23) = 4.44, p < .05$. In addition, there was an

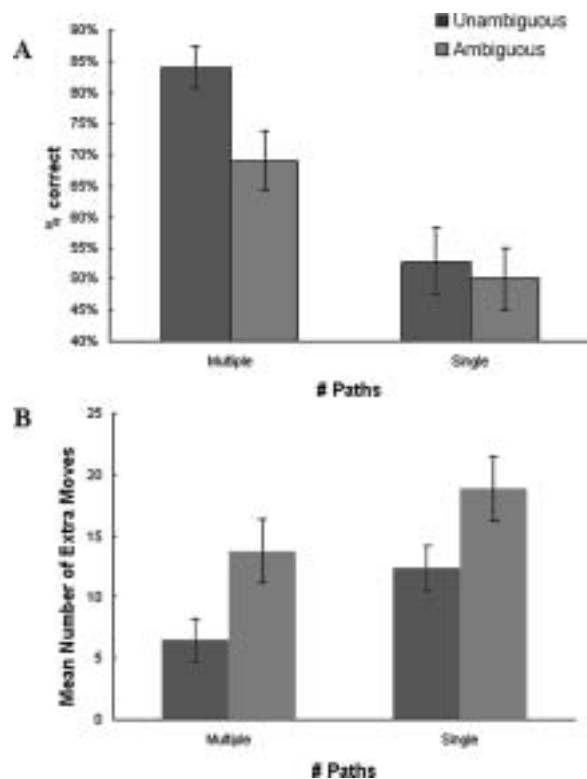


Figure 2. Accuracy results. A: percentage of trials that were solved in the minimum number of moves per condition. B: mean number of extra moves for the problems that were not solved in the minimum number of moves. The error bars depict standard error.

interaction between these two factors that showed that there was a greater effect of goal hierarchy on the multipath problems than on the single-path problems, $F(1, 23) = 6.99, p < .05$.

In addition, the number of extra moves was also subjected to a two-factor ANOVA. The ambiguous problems and the problems with only one solution path elicited a larger number of extra moves: goal hierarchy, $F(1, 23) = 24.34, p < .001$; paths, $F(1, 23) = 11.53, p < .01$; see Figure 2B. There was no significant interaction between the two variables ($F < 1$). Post hoc tests revealed that only the unambiguous problems revealed a significant effect of number of optimal solution paths, with the single-path problems eliciting more extra moves: unambiguous, $F(1, 23) = 19.12, p < .001$; ambiguous, $F(1, 23) = 2.83, p > .1$.

Total solution time

The total solution time was examined using a two-factor ANOVA for only those problems solved in the minimum number of moves (see Figure 3). The analysis revealed only a significant effect of goal

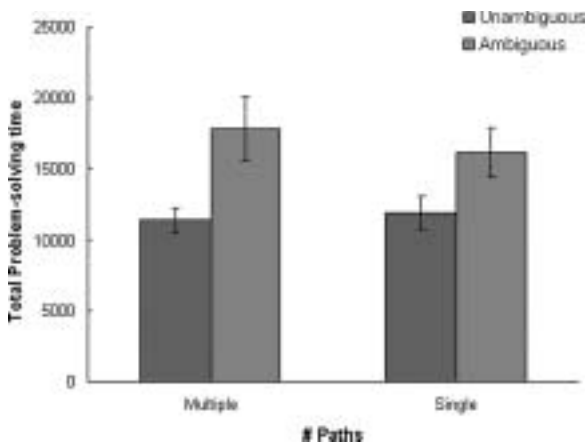


Figure 3. Total problem-solving time. Error bars depict standard error.

hierarchy with ambiguous problems taking longer to solve than unambiguous problems: goal hierarchy, $F(1, 23) = 18.02, p < .001$; paths, $F(1, 23) = 2.93, p > .1$; interaction, $F(1, 23) = 2.6, p > .1$.

Preplanning times

An ANOVA with number of optimal solution paths and goal hierarchy as within-subject factors was applied to the preplanning times only for those problems solved in the minimum number of moves (see Table 2). The results revealed a main effect of goal hierarchy with the ambiguous problems taking longer to plan (see Table 2). There was no main effect of paths ($F < 1$) or an interaction between goal hierarchy and number of solution paths. Unlike in the above analysis, post hoc tests revealed that the number of paths had no effect on either the unambiguous or the ambiguous prob-

lems: unambiguous, $F(1, 22) = 2.45, p > .1$; ambiguous, $F(1, 22) = 1.58, p > .2$.

Movement times

An ANOVA examining the movement times across trials in each condition revealed that there were no differences between trials within a condition (all p -values were greater than .25). This result suggests that there are minimal differences across trials within a condition.

The movement time for only those problems solved in the minimum number of moves was examined with a within-subjects ANOVA. There were generally longer response times for the ambiguous problems than for the unambiguous problems. Additionally, an effect of number of optimal solution paths was observed on Moves 3, 4, and 5, with the multipath problems showing a longer movement time than the single-path problems (see Table 2 and Figure 4).

Correlation analysis was performed to examine the relationship between accuracy (examining only those trials not solved in the minimum number of moves) and preplanning time for each of the four conditions. The results are shown in Table 3 and indicate that only for the ambiguous, single-path problems was there a significant correlation between preplanning time and accuracy, such that longer preplanning resulted in fewer extra moves (see Figure 5).

DISCUSSION

As expected, we found that structural differences (the goal hierarchy manipulation) in TOL

TABLE 2
The movement time results when considering only trials solved in the minimum number of moves

Move no.	<i>F-value</i>				
	<i>Main effects</i>			<i>Simple effects</i>	
	<i>Goal hierarchy</i>	<i>No. paths</i>	<i>Interaction</i>	<i>Single vs. multipath</i>	
				<i>Unambiguous</i>	<i>Ambiguous</i>
Preplanning	13.94**	<1	2.16	2.45	1.58
2	<1	<1	<1	<1	<1
3	15.48**	18.82**	3.15	16.34**	1.75
4	22.8**	11.51**	16.43**	<1	15.33**
5	2.99	15.7**	<1	3.57	26.66**
6	17.88**	<1	11.56**	8.37*	3.48

* $p < .05$. ** $p < .001$.

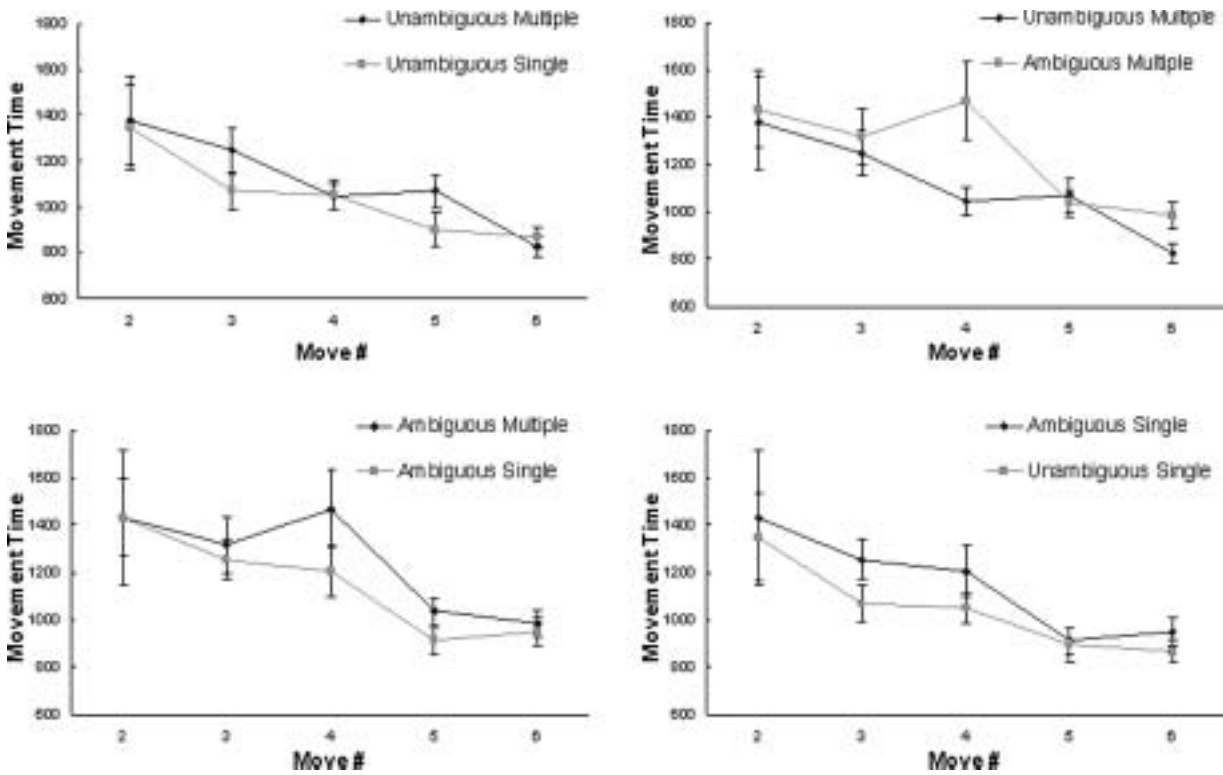


Figure 4. Movement timecourses for problems solved in the 6 moves. The left figures depict the effect of goal hierarchy while the right depicts the effect of number of paths. Error bars depict standard error.

TABLE 3

The results of the correlation between preplanning time and number of extra moves

	<i>R</i>	<i>p</i>
Unambiguous, multipath	-.2490023	>.2
Unambiguous, single path	-.2484251	>.2
Ambiguous, multipath	-.130887	>.5
Ambiguous, single path	-.6264648	=.001

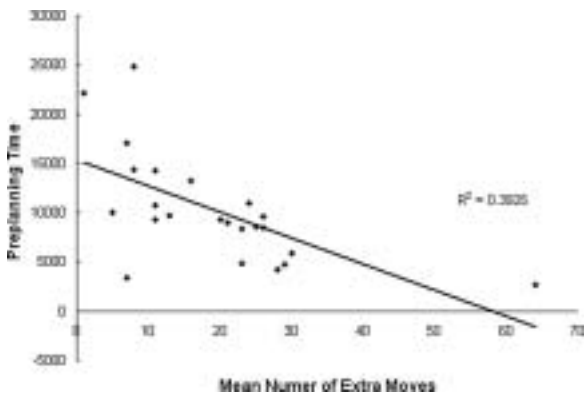


Figure 5. The correlation between preplanning time and number of extra moves for the ambiguous single-path problem.

problems significantly influenced problem-solving performance. Here, we found effects of goal hierarchy on accuracy, preplanning time, and the time to make individual moves. While an effect on accuracy and preplanning time may be expected, the effect on the subsequent movement time was not and has implications for the ability to develop a full plan prior to execution. Additionally, it was found that the number of optimal solution paths also influenced problem-solving performance. The effect of number of solution paths was a complex one. The single-path problems elicited a greater number of errors during problem solving. However, when examining those problems that were solved in the minimum number of moves, the multipath problems tended to elicit longer response times, but only at very specific points in the problem-solving process. A possible explanation for the pattern of observed results is suggested below.

Problem structure

In a previous study examining the influence of problem structure on problem solving, Kaller and colleagues (2004) found that goal hierarchy had a significant effect on preplanning time but not on movement time. In that study only three-move,

single-path problems were examined. The results of the current study provide support for the Kaller findings with the use of more demanding six-move problems. Here, it was found that goal hierarchy influenced not only preplanning time, but also accuracy and individual movement times. As shown in Table 2 and Figure 2, the time to make each individual move was significantly longer for the problems with ambiguous goal hierarchies. This is true for both the single and the multipath problems. One possible explanation for the effect of goal hierarchy on movement times and accuracy observed here, but not observed in the previous study, is the increasing working-memory demands for six-move compared to three-move problems. However, there is more than just a working-memory difference between six- and three-move problems. The planning process itself becomes more demanding when the length of the path increases. In fact, in a study by Unterrainer et al. (2004) it was found that working-memory tests, both verbal and visuo-spatial tests, failed to predict TOL performance for five- to seven-move problems. In that study participants were instructed to plan ahead, just as they were in the present study. The authors suggest that TOL performance is somewhat independent of working memory and taps planning abilities specifically. Therefore, the goal hierarchy manipulation used here manipulates planning processes, not working-memory processes.

A question that is debated is whether efficient preplanning is possible in the TOL or is TOL controlled by online planning (Kafer & Hunter, 1997; Phillips et al., 1999, 2001; Unterrainer et al., 2003, 2004). According to Phillips et al. (1999, 2001) preplanning the entire sequence is not natural, but people instead plan the beginning sequence of moves and then intersperse planning and execution. In the present study participants were told to plan their entire path before making their first move. If the entire path is planned in advance, then the goal hierarchy effect should be confined to the preplanning stage because for both the unambiguous and ambiguous problems execution involves carrying out the preplanned moves. However, not only are differences in the preplanning time observed for unambiguous and ambiguous problems, but goal hierarchy effects are observed at each move, with the exception of Move 2. The effect of goal hierarchy on the movement times suggest that planning may occur online. While it is evident from the much longer preplanning time compared to subsequent movement times that participants are indeed attempting to generate a plan, it is possible that they either regenerate or reevaluate that plan midway through execution.

A closer look at the movement time pattern suggests that it is related to the generation, or execution, of a new goal/subgoal chunk. A subgoal chunk, is defined here as a sequence of moves that achieves a subgoal. For example, in Figure 1A the first goal is to clear Bin 1. The subgoal chunk that would accomplish that goal would then be: Move the yellow ball to Bin 2; move the red ball to Bin 2; move the blue ball to Bin 3. The next goal would then be to create the goal tower. The corresponding subgoal chunk would then be: Move the red ball to Bin 1; move the blue ball to Bin 1; move the yellow ball to Bin 1. According to this sequence of goals and moves specific predictions regarding the movement times can be made with the assumption that these chunks of moves are chunked together in working memory. First, it may be that participants start with the first subgoal chunk, and then they need to either recall from working memory or replan the next subgoal chunk. Some evidence for this can be seen when examining the movement time course; it appears that for each problem type there is either a plateau or peak in the time course at Move 4. This suggests that participants have completed the execution of one subgoal chunk and are preparing for the next one. Again, an assumption made here is that the sequence of moves that make up a subgoal chunk are programmed together, and the peaks or plateaus in the time course are related to programming the next chunk. Therefore, even if participants plan the entire sequence of moves, they are stored in chunks that move together. Anderson and colleagues (Anderson, Albert, & Fincham, 2005) observed similar results in a TOH variant requiring 28 moves. The response time (RT) time course in that study correlated well with their analysis of task demands, which entailed the generation and execution of goals throughout the problem-solving process. An interesting question that deserves some consideration is whether this chunking is related to working-memory capacity. You may, for example, expect the number of moves that make up a subgoal chunk to be correlated with working-memory capacity. Further study is required to address that hypothesis.

Again, previous studies have questioned the relationship between preplanning and TOL problem solving. The results of the correlation analysis performed provide mixed support for such a relationship. The present study found that preplanning time and number of extra moves were only correlated with the more difficult, single-path problems with ambiguous goal hierarchies. The longer the preplanning time for these problems the fewer the number of extra moves. There was no significant correlation observed for the other three

problem-solving conditions. These results are mixed because they somewhat support the hypothesis proposed by Phillips et al. (2001) in that, at least for three of the four conditions, preplanning did not influence subsequent problem solving. However, the ambiguous problems elicit a correlation between preplanning time and problem-solving performance, which supports the hypothesis that people can generate a plan prior to execution and use that plan in subsequent problem solving (Unterrainer et al., 2004). The present results seem to refine the argument by suggesting that the influence preplanning has on subsequent problem-solving performance is dependent upon the problem structure. In fact, Unterrainer et al. (2004) argued this very point.

Number of optimal solution paths

A second aim of the present study was to examine the effect of the number of optimal solution paths on planning and execution processes, as well as how it may interfere with setting goal priorities. Here, it was found that the single-path problems elicited a greater number of errors. Because there is only one path to the goal, participants were more likely to choose the wrong path: either a nonoptimal path or a path that later required them to move back to the start state and begin again. In either case, choosing the wrong path resulted in an increase in the number of extra moves. This result is similar to what was observed in a previous study that used two different variants of the TOL, one with single optimal path solutions and one with two (Unterrainer et al., 2005). Like in the current study, there it was found that multipath problems revealed a greater accuracy rate and shorter planning times.

It also appears that the effect of number of paths differentially affected unambiguous and ambiguous problems, at least in the preplanning time of these two problem structures. The single-path unambiguous problems took longer to plan than the multipath unambiguous problems, while the reverse was observed for the ambiguous problems (the multipath took longer to plan than the single-path problems). However, when examining the individual moves, Moves 3, 4, and 5 show longer movement times for the multipath problems than for the single-path problems (see Figure 4), with unambiguous problems showing an effect at Move 3 only and ambiguous problems at Moves 4 and 5 only.

The differences in the location of these effects may be related to differences in the structure of the

problems. The unambiguous problems, again, have two optimal solution paths. The two solution paths separate at Move 2 and come back together at Move 5 (see Figure 1A). However, the completion of a subgoal chunk occurs at Move 3 for both the single-path and multipath problems. Additionally, while the moves are different, there are no differences in the number of alternative moves at Move 3 for the two optimal solution paths for the unambiguous multipath problems. The only explanation for the increased movement time is that participants may have discovered the alternative route during preplanning for the multipath problems, and they are still comparing the two paths at the completion of a subgoal to ensure that they chose the more efficient path.

The ambiguous multipath problems have three optimal solution paths (see Figure 1B). Two of the three paths separate at Move 4 and rejoin at Move 6. Another two of the three paths separate at Move 1 and rejoin at Move 4. The final path couple separate at Move 1 and do not rejoin until Move 6. It seems that Move 4 is a critical move for the ambiguous multipath problems. Move 4 is also where the movement time course peaks for this problem type. Again, assuming that participants have generated multiple solution paths during preplanning, and are considering multiple paths during problem solving (participants were implicitly told to consider multiple paths), Move 4 is the point where the evaluation of the paths may take place. Move 4 is the beginning of a new subgoal chunk, and if there are multiple ways to execute that chunk then the participants should be expected to evaluate them at this time.

To summarize the effect of number of optimal solution paths, it seems as though the effect is perpetuated throughout the problem-solving process. It may be that knowing that there are multiple solution paths and possibly what those paths are requires you to check that you are using the appropriate path. The checking seems to occur after the completion of a subgoal sequence and not during the execution of that sequence. At this point it is difficult to definitively assign an explanation for the differential effect number of paths has on the ambiguous and unambiguous problems. This is because the number of optimal solution paths appears to interact with the increased demand on planning processes associated with goal hierarchy. Given that one of the characteristics of the TOL variant used here is that all six-move unambiguous multipath problems have two optimal solution paths, and all six-move ambiguous multipath problems have three optimal solution paths, it is difficult to completely disentangle the relationship between goal hierarchy and number of optimal solution paths.

CONCLUSION

The results of the present study demonstrate that problem difficulty can be manipulated while holding the minimum number of moves constant. The problem structure manipulated here was goal hierarchy, and it was found to significantly influence planning as well as execution processes. We have also demonstrated that, although preplanning is performed, it does not always influence subsequent task performance. Planning does appear to occur online, and it appears to occur in chunks, meaning that we plan a small sequence of moves that allows for the achievement of a goal and then tackle the next goal. Additionally, the current results show that the number of optimal moves also has a significant impact on both the processes associated with planning and those associated with the execution of that plan. It appears as though when planning, both preplanning and online planning, alternative routes are compared.

As a result of the current findings as well as previous work (Kaller et al., 2004), we suggest that using simply the minimum number of moves in TOL problems to characterize problem difficulty be reevaluated. This may be an important consideration given that many of the TOL tests used to assess executive functioning in clinical populations simply use the minimum number of moves as a measure of difficulty. Taking these structural parameters into consideration may provide for greater insight into the processes that underlie planning.

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