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Authors

Morgan, Phillip
Patrick, John
Patrick, Tanya

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Increasing Information Access Cost to Protect Against Interruption Effects during Problem Solving

Phillip L. Morgan (MorganP4@Cardiff.ac.uk)
John Patrick (PatrickJ@Cardiff.ac.uk)
Tanya Patrick (PatrickTP3@Cardiff.ac.uk)
School of Psychology, Cardiff University, Tower Building,
Park Place, Cardiff, CF10 3AT, UK

Abstract

The aim of this experiment was to examine whether increasing the cost of accessing the goal-state during problem solving would induce a more internalized strategy that would protect against the negative effect of interruption. The soft constraints hypothesis (Gray, Sims, Fu & Schoelles, 2006) predicts that a more memory-based strategy will be developed with increasing information access cost (IAC). Three levels of access cost were used in the Tower of Hanoi (ToH) with three types of interrupting task (simple ToH, mental arithmetic and a blank screen control). Increasing access cost to a mouse movement and a few seconds delay to view the goal-state encouraged a strategy that not only improved resumption from memory but also reduced the number of moves required to solve the primary task. These effects came at no extra time cost and occurred irrespective of the type of interrupting task. The theoretical implications of these findings are discussed together with issues of using access cost as a method for alleviating the negative effects of interruption.

Keywords: Interruption; Problem Solving; Goal-State Access Cost

Introduction

Interruptions are intrinsic to our everyday and working lives (e.g., telephone calls, emails), and although often useful (e.g., responding to another important task), they are also often associated with performance decrements when returning to the interrupted task. Difficulties include: problems remembering what one was doing or intended to do prior to being interrupted (e.g., Edwards & Gronlund, 1998; Morgan, Patrick, Waldron, King & Patrick, 2009); and delays in resuming the interrupted task (e.g., Hodgetts & Jones, 2006; Monk, Trafton & Boehm-Davis, 2008). Whilst these issues are sometimes tolerable (e.g., when taking a telephone call whilst buying groceries), interruptions can be a nuisance, expensive or even life threatening in many other contexts, including, offices, aircraft flight-decks, and hospitals (see Trafton & Monk, 2008). Thus, investigating methods for minimizing interruption effects has become an important topic. Methods include: using an ‘interruption lag’ to briefly delay the onset of an interruption and allow an opportunity to prepare for resumption of a problem solving task (Hodgetts & Jones, 2006); and a reminder cue to support memory of a delayed intention in a prospective memory task (McDaniel, Einstein, Graham & Rall, 2004). A recent study by Morgan et al. (2009) developed another method that involved increasing goal-state access cost (the time, physical and mental effort costs associated with accessing information). This encouraged a more memory-based strategy that was effective in protecting against forgetting following interruption. The aim of this paper is to investigate the efficacy of this method in a problem solving task rather than the copying task used by Morgan et al. (2009).

The predicted advantage of increased access cost on promoting a more internal cognitively-based strategy derives from the soft constraints hypothesis (Gray et al., 2006). This theory posits that whilst certain elements of a task environment are fixed (i.e., hard constraints) and dictate what behavior is possible, task strategies are flexible and therefore adapt in a rational manner. People strive to minimize the time spent performing tasks at a local rather than global level (Gray et al., 2006), so strategy adjustments are made at the 1/3 to 3-second level of task performance favoring those that are more effective at this millisecond level (Gray & Boehm-Davis, 2000). On one hand, if information is readily available in the task environment, a strategy that relies less on internal memory (which is fallible and subject to error) will prevail (e.g., Anderson & Douglass, 2001). In contrast, if there is an unacceptable cost associated with accessing information in the task environment, cognition will adapt and adjust to a more memory-based strategy to minimize this cost.

Such strategy change has been demonstrated in a variety of studies (Gray & Fu, 2004; Gray et al., 2006; Morgan et al., 2009; Waldron et al., 2007) using the Blocks World Task (BWT) developed by Ballard, Heyhoe & Pelz (1995), that involves copying a target pattern of colored blocks to a workspace window. Increasing the cost of accessing the target pattern with a mouse movement and a brief time delay induced a shift to a more memory-based strategy (e.g., Gray & Fu, 2000; Gray et al., 2006) and improved recall of information (Waldron, Patrick, Morgan & King, 2007). Morgan et al. (2009) found that such an induced memory-based strategy protected against forgetting following both visuo-spatial copying and mental arithmetic interrupting tasks. This was particularly effective when the interruption occurred on approximately half of the trials.

In contrast, little is known about the effect of goal-state access cost on problem solving. Some studies have manipulated the availability and effort required to use the task environment as an external memory resource. For example, the use of internal memory increased when the ability to make paper notes was made more difficult whilst solving demanding mental arithmetic problems (Cary & Carlson, 2001). Similarly, when the current-state had to be requested during performance of 'balls and boxes' problems, participants tended to execute more moves per request (Pfeiffer, 2004). Also, O'Hara and Payne (1998) demonstrated how increasing the cost of implementing an action during problem solving leads to improved planning. The results from these studies suggest increased use of internal memory to avoid additional costs of interacting with the environment. One recent problem solving study found that High goal-state access cost led to more 'planning before action' as opposed to 'planning during action' (Waldron, Patrick & Duggan, unpublished) although it had no effect on number of moves to solution. However the effect of High goal-state access cost on mitigating the negative effect of interruption has not been examined during problem solving.

Experiment

To fill this research gap, the aim of the experiment was to examine whether increasing goal-state access cost induces a more memory-based strategy in a ToH task and whether such a strategy can improve performance following interruption. It was predicted that High access cost would accomplish this by encouraging a more internalized rather than display-based strategy with more planning before action (Davies, 2003; Waldron, Patrick & Duggan, unpublished).

There were two subsidiary aims. First, Morgan et al. (2009, Experiment 3) demonstrated that High access cost induced a memory-based strategy that was powerful enough to abolish the effects of forgetting following different types of interrupting tasks compared to a no interruption condition, even when one task (another BWT) arguably had similar processing requirements to the primary task. There is mixed evidence regarding the effects of interruption similarity on post-interruption performance. Some studies report greater disruption following a similar interrupting task (e.g., Edwards & Gronlund, 1998; Gillie & Broadbent, 1989) whereas others argue against this so called 'interruption similarity' effect (e.g., Latorella, 1996). Given that it is difficult to unequivocally separate tasks on dimensions of similarity, we examined the effects of increasing goal-state access cost on performance following two different types of interrupting tasks: one involving another ToH (arguably similar to the primary task) and the other involving mental arithmetic.

Second, we wanted to assess whether the typical cost of High access cost on reducing speed of completing the BWT (Morgan et al., 2009) would be less pronounced or even eliminated in the ToH. Performing the BWT under a High access cost places a high demand on memory and participants spend time encoding and rehearsing block information, suffering the time cost of uncovering the goal-state at each visit, and making more move errors that have to be corrected. In contrast, the ToH is not as memory demanding given that the goal-state often consists of a small array of objects (e.g., 4-discs) that are bounded by a simple constraint (e.g., a larger disc cannot be placed on top of a smaller disc). Also, the hierarchical nature of the ToH in terms of goal and subgoals means that many moves are interdependent, and therefore the goal-state does not need to be re-visited as often as in the BWT. Furthermore, the proposed benefit of High goal-state access cost in the ToH is due to its encouragement to develop a more effective problem solving strategy that should lead to fewer moves and possibly reduced time to solve the problem.

Method

Participants

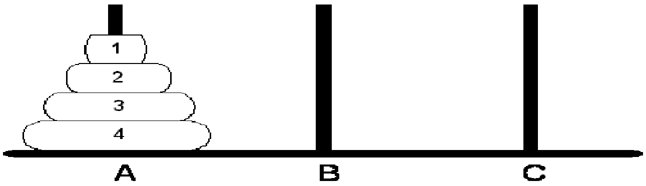
Fifty-four Cardiff University Psychology students participated for course credit and were randomly assigned to one of three goal-state access cost conditions. There were six men and forty-eight women with an age range of 18 to 37 years (*M* = 20.56, *SD* = 2.95).

Materials, Design & Procedure

There were 18 primary task four-disc ToH problems, each with a different start and goal-state disc configuration (see Figure 1 for an example start-state). Disc movement was controlled by clicking on a disc on one peg (e.g., A), holding down the mouse button, and dragging the disc to a destination peg before releasing the mouse button (e.g., at B or C). If a larger disc was dragged over a smaller disc, the larger disc would be returned to its source peg and a message reading 'illegal move' would appear on the screen. All primary task ToH problems required a minimum of 15 moves for error-free completion and all major subgoals occurred at the same point within the solution sequence (if solved error-free: subgoal 1, moves 1 – 8; subgoal 2, moves 9 – 12; and subgoal 3, moves 13 – 15). The main subgoals within the ToH task involve getting the largest-out-of-place discs to their goal destination peg(s) in the order 'largest first' through to 'smallest last'.

Figure 1. An example of the start-state of a four disc ToH task

Note. Disc numbers are used to represent colors (1 = green, 2 = blue, 3 = yellow, and 4 = red)



Goal-state access cost was manipulated between-subjects on three levels: Low (goal-state always visible), Medium (goal-state covered with a grey mask with a mouse movement to uncover) and High (as Medium but with an additional 2.5-second lockout cost to uncover). Each of nine ToH problems was interrupted once with one of three different interruption types (manipulated within-subjects). The ToH interruption consisted of 3-disc ToH problems that could be solved in a minimum of seven moves using the same disc movement procedure as in the primary task. The mental arithmetic (MA) interruption involved solving a series of self-paced double-digit addition problems (e.g., 34 + 45 = ??). Answers were entered using a keyboard. In the control condition (referred to as blank screen interruption hereafter), there was no task during the interruption. Each interruption occurred immediately following the first move of the first, second or third major subgoals, giving three interruption points. Both interruption task type and interruption position were counterbalanced.

Two types of measure were used to examine the effects of goal-state access cost and interrupting task on the ability to resume the primary task from memory. First, we calculated the number of interrupted trials resumed without first re-visiting the goal-state and, for those trials, the number of moves executed subsequently. Second, we calculated both the number of moves and the time required to complete the ToH problem following interruption. Given that interruptions were equally distributed across the three points of interruption, fair comparisons could be made between both the different levels of access cost and the different interrupting tasks. Finally, it was important to confirm that any benefit of increased goal-state access cost on performance following interruption was due to increased use of a more internalized problem solving strategy with reduced reliance on the external problem space. For this we used an important measure of planning in problem solving (e.g., Davies, 2003, 2005; Ward & Allport 1997), which was the amount of time spent at the beginning of a ToH problem before the first move was executed. This was predicted to increase with increasing access cost.

Participants were tested individually. They were instructed on task procedures and informed that they could be interrupted at any time. The main experiment started after completion of one non-interrupted 15-move practice trial and one attempt at performing each interrupting task. The experiment lasted approximately 30 minutes.

Results and Discussion

First, the effects of goal-state access cost and interruption type on the ability to resume the primary ToH task from memory were considered, followed by an examination of their effects on various post-interruption performance measures. Finally, we assessed whether any beneficial effect of High access cost on these performance measures could be accounted for by participants using a more memory-based problem solving strategy.

Effects of Goal-State Access Cost and Interruption Task on Performance after Interruption

We predicted that the main benefit of a higher access cost would be a tendency to adopt a more internalized problem solving strategy with participants choosing to rely less on the external problem space, even following interruption. As such, it was anticipated that participants in the High access cost condition would resume the primary task without revisiting the goal-state (and suffering the associated time cost) more often than the Medium access cost condition. (Note that the Low access cost condition could not be considered for any resumption measure because the goal-state was permanently uncovered.) The results supported this prediction (Table 1) with a 2 (goal-state access cost: Medium and High) x 3 (interruption type: blank screen, ToH, MA) ANOVA revealing that more trials were resumed from memory by participants in the High compared to the Medium access cost condition, $F(1, 34) = 67.43$, $MSE = 3.28$, $p < .001$. There was also a main effect of interruption type, $F(2, 68) = 9.47$, $MSE = 6.57$, $p < .001$, due to less use of the goal-state to aid resumption following a blank screen interruption compared to a ToH interruption. Furthermore, and as predicted, Bonferroni post-hoc tests revealed that participants in the High access cost condition resumed more often without first viewing the goal-state than those in the Medium access cost condition following all interruption types ($ps < .001$).

Table 1. Effect of goal-state access cost and interruption task on resumption performance

	Goal-State Access Cost		Interruption Type		
			Blank	ToH	MA
Number of trials resumed without re-visiting the goal-state (max = 3)	Med	*M*	1.17	.11	.61
		SD	.86	.32	.78
	High	*M*	2.56	1.46	2.28
		SD	1.17	.94	.83
Number of participants resuming at least one trial without viewing goal-state	Med		13/18	2/18	8/18
	High		17/18	16/18	17/18
Number of moves executed without re-visiting the goal-state	Med	*M*	4.19	-	2.57
		SD	1.56	-	1.97
	High	*M*	6.78	-	6.55
		SD	3.30	-	3.87

Therefore it is evident that participants in different access cost conditions adopted different resumption strategies involving the need to view (or not) the goal-state to resume. For example, most participants in the Medium access cost condition were unable to resume at least one ToH interruption trial without first revisiting the goal-state window (Table 1). In contrast nearly all participants in the High access cost condition resumed at least one ToH trial from memory. This demonstrates the protective effect of High goal-state access cost on memory for the goal-state and/or a future move(s) following a ToH interruption *and* the ineffectiveness of Medium goal-state access cost following the same type of interruption. This beneficial effect of High access cost was reduced with the two other interrupting tasks although it was still apparent for an MA interruption (Table 1).

Another indicator of participants relying less on the external display and more on an internal representation to continue an interrupted task is the number of moves they make before re-inspecting the goal-state (Table 1). A 2 (goal-state access cost) x 2 (interrupt type: blank screen and MA) ANOVA revealed a main effect of goal-state access cost, $F(1, 22) = 7.09$, $MSE = 7.54$, $p < .05$, with participants in the High access cost condition making more moves after interruption before goal-state re-inspection than those in the Medium access cost condition. There was no effect of interruption type and goal-state access cost and interruption type did not interact ($ps > .05$).

These results are testimony to the marked effect of High goal-state access cost on the ability to maintain an internal representation of the goal-state and/or a future move or series of moves throughout the course of an interruption, even when interruption involved a different task.

Whilst the above measures concerned interruption trials that were resumed without first viewing the goal-state window (and are thus restricted to the Medium and High goal-state access cost conditions), it is also important to establish the effects of all three levels of access cost on post-interruption performance (Table 2). Specifically, we were interested whether High access cost with its more internal memory-based strategy (1) led to fewer moves and (2) affected the time to complete interrupted ToH problems.

Participants in higher access cost conditions completed interrupted ToH problems in fewer moves (Table 2). A 3 (goal-state access cost: Low, Medium and High) x 3 (interruption type: blank screen; ToH, MA) ANOVA confirmed a significant main effect of goal-state access cost $F(2, 51) = 4.35$, $MSE = 2.53$, $p < .05$, $f = .41$ with participants in the High access cost condition completing problems in fewer moves than participants in the Low access cost condition ($p < .05$). However, participants in the High access cost condition did not perform significantly better than those in the Medium access cost condition ($p > .05$), and participants in the Medium access cost condition did not perform better than those in the Low access cost condition ($p > .05$). There was a non-significant main effect of interruption type ($p > .05$) and a non-significant interaction ($p > .05$).

Time to complete problems following interruption was similar across goal-state access cost conditions (Table 2), and there was a non-significant main effect ($p > .05$). There was, however, a significant effect of interruption type, $F(2, 102) = 7.77$, $MSE = 52.77$, $p < .01$, $f = .39$. Not surprisingly, participants were significantly faster to complete following a blank screen than a ToH interrupting task ($p < .01$) and were marginally faster following mental arithmetic than a ToH interrupting task ($p = .06$). Goal-state access cost and interruption type did not interact ($p > .05$).

Table 2. Effect of goal-state access cost and interruption type on performance following resumption

	Goal-State Access Cost		Interruption Type		
			Blank	ToH	MA
Number of moves to complete the primary task following interruption	Low	*M*	10.39	11.70	11.26
		SD	2.98	3.49	3.05
	Med	*M*	9.52	10.93	10.19
		SD	1.57	3.20	2.33
	High	*M*	9.28	9.89	9.52
		SD	2.25	1.93	2.29
Time to complete the primary task following interruption (s)	Low	*M*	20.65	25.79	22.16
		SD	9.28	8.84	8.18
	Med	*M*	19.09	23.19	21.36
		SD	7.79	9.23	9.52
	High	*M*	17.28	24.42	19.74
		SD	7.38	12.76	5.97

Thus, the more memory-based strategy associated with High goal-state access cost was sufficient to effect an improvement in problem solving efficiency following interruption compared to a Low access cost. In contrast, the cost of a mouse movement in the Medium access cost condition was not sufficient to improve performance compared to the Low access cost condition. Furthermore, the improvement under a High access cost on resumption *and* performance thereafter comes at no extra time cost compared to lower access cost conditions. This is especially encouraging given the extra time cost associated with such a condition in a more memory-demanding visuo-spatial copying task (e.g., Morgan et al., 2009).

Effects of Goal-State Access Cost on Planning

It is important to confirm that the improvements in performance following interruption during High goal-state access cost can be accounted for by a change of task strategy. One important measure of planning is the amount of time taken to execute the first move at the start of a ToH, which we predicted would be greatest in the High access cost condition. A significant main effect of goal-state access cost, $F(2, 51) = 4.82$, $MSE = 4.59$, $p < .05$, $f = .44$, revealed that participants in the High access cost condition indeed took more time to execute the first move ($M = 6.31$, $SD = 2.7$) than those in Medium and Low access cost conditions, $ps < .05$ ($M = 4.53$, $SD = 1.45$ and $M = 4.27$, $SD = 2.08$ respectively). Time spent planning in the Medium and Low access cost conditions did not differ statistically ($p > .05$).

General Discussion

The current experiment demonstrates the efficacy of imposing higher costs on accessing the goal-state in problem solving to promote a more efficient memory-based strategy that protects against the negative effects of different types of interruption. High goal-state access cost was superior to lower access cost conditions on nearly all measures following any type of interrupting task. The benefit of a High access cost to induce a more memory-based strategy to protect against forgetting following interruption has been demonstrated with a simple BWT copying task (Morgan et al., 2009), but this paper highlights for the first time how these effects extend to a problem solving task. This is especially interesting given the different nature of the BWT and a ToH problem solving task. The BWT has a relatively flat and repetitive goal structure (e.g., locate a block in one position and move it to another position), whereas the ToH has a hierarchical goal structure and can be performed using a variety of different strategies that usually become more sophisticated with practice (e.g., Anzai & Simon, 1979).

The findings provide further support for the soft constraints hypothesis (e.g., Gray et al., 2006), particularly its claim that strategy selection is dependent upon the time costs imposed by interacting with the external task environment. We have shown that when the ToH goal-state is masked and cannot be viewed without suffering a mouse movement and a brief time cost, problem solving strategy becomes more internalised and less display-based. Whilst this strategy selection is based upon a very subtle change to the task environment, it is powerful enough to protect against forgetting following interruption and improves problem solving efficiency.

The results can also be interpreted within the theoretical framework of the memory for goals model (Altmann & Trafton, 2002). This is a model of goal suspension and resumption that posits: for a goal to govern behaviour it has to be repeatedly *strengthened* so that its activation level within internal memory exceeds that of an interference threshold set by all other goals in memory. A goal must be *primed*, that is, associatively linked to a reminder cue (either externally or internally based) that must be available both immediately prior to and following interruption, otherwise the goal will decay and become forgotten. Upon encountering this cue again, the decaying representation of the suspended goal will be reactivated such that it again governs behavior. Our data suggest that suspended goals may have undergone a greater amount of strengthening in the High access cost condition and we may speculate that the current-state disc configuration might have provided adequate priming cues. However, the memory for goals model suggests that an interruption lag is a critical period to strengthen and prime a to-be-suspended goal so that it can be retrieved from memory after interruption. The current findings, together with those reported in Morgan et al. (2009), suggest that an interruption lag may not be critical if the task performer is equipped with a more memory-based strategy *throughout* performance of the primary task. High goal-state access cost is a subtle yet powerful method to induce such a strategy and thus may either be an alternative method to an interruption lag or a complementary method to support its proposed benefit.

The findings are also important from a practical perspective, especially regarding principles relating to cognitive engineering and display design. These principles stress the importance of making available as much information as possible to perform a task (see Wickens & Hollands, 2000), at least within the realm of human capabilities (e.g., Rasmussen & Vicente, 1989). For example, ecological interface design recommends that complex relationships between variables should be made immediately available and information within the interface should be easily extractable (Vicente & Rasmussen, 1992). Similarly, information fusion involves synthesising information from a wide range of sources and displaying it to the user in an immediately available format (e.g., Dasarathy, 2001). Whilst adopting these principles has benefit in many situations, they also risk a passive and more display-based approach to monitoring and processing information that may ultimately result in the user moving ‘out-of-the-loop’ (e.g., Bainbridge, 1987). A recent study by Waldron et al. (2008) using a flight simulation found that making positional information temporarily rather than permanently available improved memory for aircraft location. Given the additional findings of the current experiment and related studies (e.g., Morgan et al., 2009; Waldron et al., 2007) we perhaps radically suggest that paradoxically making information harder to access may sometimes improve performance, such as when resuming some tasks following interruption. This will depend on what is the criterion measure of performance and the advantage will be greatest when recall is important to post-interruption performance. There are of course exceptions to this suggestion. For example, it is unlikely that the benefits of increased goal-state access cost would outweigh the costs of having to continually access information in fast-paced, safety-critical task environments such as an aircraft flight-deck.

Future experiments will be necessary to fully test the boundary conditions associated with the benefit of increased goal-state access cost in problem solving and other task environments, both with and without interruptions. Furthermore, it is practically important to compare the advantages and disadvantages of using access costs with other methods for mitigating interruption effects.

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Acknowledgments

Phillip, L Morgan & John Patrick are at the School of Psychology, Cardiff University, UK, CF10 3AT.

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Correspondence should be addressed to Phillip L. Morgan, School of Psychology, Cardiff University, Tower Building, Park Place, Cardiff, CF10 3AT. E-mail may be sent to MorganP4@cardiff.ac.uk.