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Moves in the World Are Faster than Moves in the Head: Interactivity in the River Crossing Problem

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Abstract

In solving a variety of problems people interact with their external environment, often using artefacts close at hand to supplement and augment their problem solving skills. The role of interactivity in problem solving was investigated using a river-crossing problem. All participants performed the task twice, once in a high interactivity condition and once in a low interactivity condition. Moves to completion were higher in the high interactivity condition but latency per move was much shorter with high than with low interactivity. Moves in the world were easier to implement than to simulate mentally and acted as epistemic actions to facilitate thinking. In addition, when participants experienced the low interactivity version of the task second, their performance reflected little learning. However, when the high interactivity version was completed second, latency to solution and latency per move were substantially reduced. These results underscore the importance of investigating problem solving behaviour from a distributed cognition perspective.

Keywords: Problem solving, interactivity, epistemic actions, distributed cognition

Introduction

Scientists and lay people alike naturally create and build artefacts or recruit existing ones to help them solve problems. To be sure, artefacts such as calculators, data management software, computers can facilitate complex computations. But others, of more modest complexity, such as pen and paper, can help articulate and structure thinking. Space itself is a tool that can facilitate thinking, that is it can be structured, designed (and redesigned) such as to make thinking easier (Kirsh, 1995, 1996, 2010). Thus solving jigsaw puzzles involves physically juxtaposing different pieces to gauge their fit; in Scrabble, letter tiles are physically rearranged to facilitate word production; in Tetris, tetrominoes are physically rotated to determine their optimal place along a line. And beyond puzzles and games, experts structure an external environment to support thinking. Scientists use physical objects and their arrangement in space to formulate and test hypotheses: Watson (1968, pp. 123-125) describes how he cleared his desk, cut out shapes corresponding to the four nucleobases, and manipulated them until he saw which ones could be paired to hold the double helix together. Artefacts recruited in thinking are rich, varied and modifiable. Their recruitment is at times strategic, such that their users actively engage in their design and engineer their function, and at others, opportunistic, that is they are picked up from the environment in an ad hoc fashion to help solve a problem, capitalizing on a fortuitous interaction.

From a distributed cognition perspective, thinking is the product of a cognitive system wherein internal and external resources are coupled to create a dynamic, fluid, and distributed problem representation (Villejoubert & Vallée-Tourangeau, 2011; Weller, Villejoubert, & Vallée-Tourangeau, 2011). The nature of the external resources recruited in thinking and their functional role are guided by principles of cognitive economy, effort and efficiency (Clark, 1989; Kirsh, 2010). Actions complement and augment thinking by providing new information, unveiling new affordances, and can sometimes serve to create a more cognitively congenial problem presentation (Kirsh, 1996). Through the creation, recruitment and manipulations of artefacts, new perspectives are gained, encouraging the development or retrieval of problem solving strategies, and improving the prospect of solving the problem (Magnani, 2007). As the environment shoulders some of the representational and computational burden, valuable cognitive resources such as working memory capacity and executive functions may be freed to draw on stored knowledge or develop new solutions (Magnani, 2007). For example, recent work on mental arithmetic indicates that people are more accurate, more efficient, and create more congenial interim totals when they can manipulate number tokens that configure the problem presentation, than when they perform the mental arithmetic without (Vallée-Tourangeau, in press).

River Crossing

Transformation problems have been the focus of research in cognitive psychology for the past 50 years. In these problems, a well-defined space connects an initial and a goal state. Legal moves are defined in terms of simple rules and enacted with simple operators. Participants must reach the goal state by transforming the initial state through a series of intermediate states. A well-studied class of transformation problems are river-crossing problems. In these problems, objects (people, animals, or things) must be carried from one "riverbank" to another on a "boat" but with a set of constraints on moves that can be selected to reach the goal. A common version involves three missionaries and three cannibals (Reed, Enrst, & Banerji, 1974; or three hobbits and three orcs, Thomas, 1974). In transporting all cannibals and missionaries from one bank to the other, cannibals must not outnumber missionaries or either bank. The boat can take at most two passengers, and at least one. The problem space is relatively narrow since illegal moves cannot produce blind alleys of any depth (Reed et al., 1974) and can be completed in 11 steps. In different versions, problem difficulty is a function of the rules that constrain the number of objects that can be moved at any one time, which combinations of objects are allowed on the boat, and which combinations can be left on either bank. The number of objects and the rules that govern their transport map out a problem space that links the initial state with all objects on one side of the river to a goal state with all objects on the other riverbank. Cognitive psychologists have used this task as a window onto problem solving, particularly planning (Greeno, 1978), search and move selection (Reed et al., 1974; Simon & Reed, 1976). As such river crossing problems have been used as a testing platform for a number of process models of search and move selection, strongly influenced by developments in AI (Greeno, 1978; Simon & Reed, 1976).

The river-crossing task involves moving people or things across a surface and as such foregrounds the importance of interacting with an external task representation. However, interactivity in river crossing problem solving has never been the explicit focus of investigation. The manner with which the river-crossing task has been implemented varies a great deal across studies. For example, Reed et al. (1974) used different types of coins to represent missionaries and cannibals. Jeffries et al. (1976) developed a basic computer interface where participants typed in the objects they wanted to put in the boat on a given crossing. The interface accepted only legal moves and updated the simple representations (often with letters and numbers, such as '3M' for three missionaries) on either side of the riverbank. Participants kept on typing in their moves until they managed to transport all objects from one bank to the other. Knowles and Delaney (2005) designed a more realistic interface with icons representing travellers against a backdrop of a river with two banks and a boat. Participants selected moves by clicking on the travellers, which then appeared next to the boat on the screen. In all these instances participants were never offered a three-dimensional work surface on which objects transparently corresponding to the scenario protagonists are manipulated and moved by hand. In contrast, developmental psychologists who worked with the river crossing task, being less sanguine about 'formal operations' presumably, have taken care to design rich interactive thinking environments with physical materials representing the boat, the river, and figurines corresponding to the cover story characters (e.g., Gholson, Dattel, Morgan, & Aymard, 1989).

A more explicit experimental focus on interactivity may unveil interesting aspects of problem solving performance. For example, there is evidence that in other transformation problems interactivity substantially transformed problem solving behaviour. Vallée-Tourangeau, Euden and Hearn (2011) reported that mental set is significantly reduced in Luchins's volume measurement problems when participants interact with an actual physical presentation of the problem. The manipulation of water jars created a dynamic problem representation revealing solutions that were not simulated mentally. The selection of moves was guided and governed by three-dimensional perceptual feedback and participants were less likely to persevere using a more complicated solution for the test problems. In a river-crossing task, interactivity may help participants work out the quality of different moves not by simulating their consequences mentally, but rather by simply completing the move and observing the results. Such moves then are 'epistemic actions' (Kirsh & Maglio, 1994)—moves that may not, in themselves, necessarily help narrow the gap with the goal state, but rather provide information as to what to do next. As such, move selection can be opportunistic, although not necessarily mindless; rather the strategic consequences of a certain move can simply be observed. Kirsh and Maglio (1994) demonstrated that it is faster and easier to physically rotate the tetrominoes in Tetris than to simulate their rotation mentally, leading to better and more efficient problem solving behaviour. In a similar vein, moves in the world, rather than moves in the head, may help participants solve river-crossing problems more efficiently as the reduced cognitive costs of physical moves will enable them to select more moves more quickly, than they would if they were completing the task with a non-interactive problem presentation.

The Present Experiment

The present experiment examined performance in the river crossing problem when presented with or without artefacts as an aid to solution. This was measured in terms of number of moves, latency to completion and latency per move. In a high interactivity condition, the problem was presented with a board, a raft and six figurines: Participants had to move the raft and the figurines across the board to register a move until they had moved all six figurines from one bank to the other. In a low interactivity version, the problem was described on a piece of paper and participants were asked to verbalise the moves they would make to reach the goal. They performed the problem twice, once with the high interactivity version and once with the low interactivity version; the order was counterbalanced across participants. This experiment employed a mixed design with interactivity level as the repeated measures factor and order—low interactivity first, high interactivity first—as the between subjects factor. As moves can act as epistemic actions, we predicted that participants would produce more moves, would solve the problem more quickly and that hence latency per move would be shorter in the high compared to the low interactivity condition. We also predicted that participants would complete the second presentation of the task more quickly than the first since they would be familiar with the procedure and may well exploit an episodic record of their trajectory to help them select better moves, and select them more quickly. A high interactivity problem solving environment may more clearly showcase evidence of learning because of the ease and speed with which moves can be made in the world.

Method

Participants

Sixty-four university undergraduates participated in the experiment in return for course credits. Due to testing errors the data from three participants were incomplete, therefore unsuitable for analysis. Of the remaining sixty-one participants, nine did not complete the river crossing problem and were excluded from further analyses. The final sample was composed of 52 participants (45 females, 7 males, M_{age} = 21.4, SD = 5.1)

Procedure

Chickens and wolves were the protagonists in the river-crossing scenario used for this experiment. The objective was for the six animals to be transported from the left riverbank to the right one. The selection of a move had to comply with the constraints and rules of the problem. The same instruction sheet explaining the objective of the task and the rules of the problem was used for both conditions and could be read by the participants throughout the duration of the task. The sheet read:

> Three wolves and three chickens on the left bank of a river seek to cross the river to the right bank. They have a boat which can carry only two animals at a time, but there must always be an animal on the boat for it to move.
>
> However if at any time the wolves outnumber the chickens on either bank the wolves will eat the chickens. Thus you cannot move the animal(s) in a manner that will result in the wolves outnumbering the chickens on either bank.
>
> The goal of the task is to move all the animals from the left bank to the right bank.

In the low interactivity version of the task, the researcher transcribed each move as verbalised by the participant onto a record sheet. The record sheet was a simple representation of the raft between the left and right banks of the river, with slots to record the nature and number of the animals on either side (which was denoted with a 'C' for chickens and 'W' for wolves; see Fig. 1); each page represented only one move. At any one time, participants could only inspect their previous move as they dictated their next move to the experimenter. As soon as the next move was dictated, the sheet with the previous move was turned over. Thus participants could not inspect a historical record of previous moves. Illegal moves proposed were noted, but the experimenter did not transcribe the move on the recording sheet. Rather, participants were invited to re-read the task instructions to discover why such a move was not allowed.

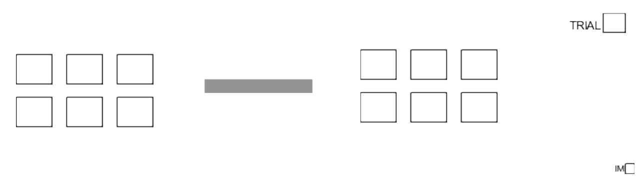

Figure 1: Record sheet for the river crossing moves in the low interactivity condition.

The high interactivity version of the task involved the use of six plastic figurines, three wolves (9cm x 7cm x 2cm) and three chickens (4cm x 5cm x 1.5cm), one pop-stick raft (9cm x 6cm) and a painted board (60cm x 45cm) representing the river and banks (see Fig. 2). As the participants interacted with the artefacts, the experimenter recorded the moves, but this record was never shown to the participants. An illegal move prompted the experimenter to instruct participants to move the raft and the animals back to the previous state and, as in the static condition, they were invited to re-read the instruction sheet to determine which moves were possible.

Figure 2: Board, raft and figurines in the high interactivity condition.

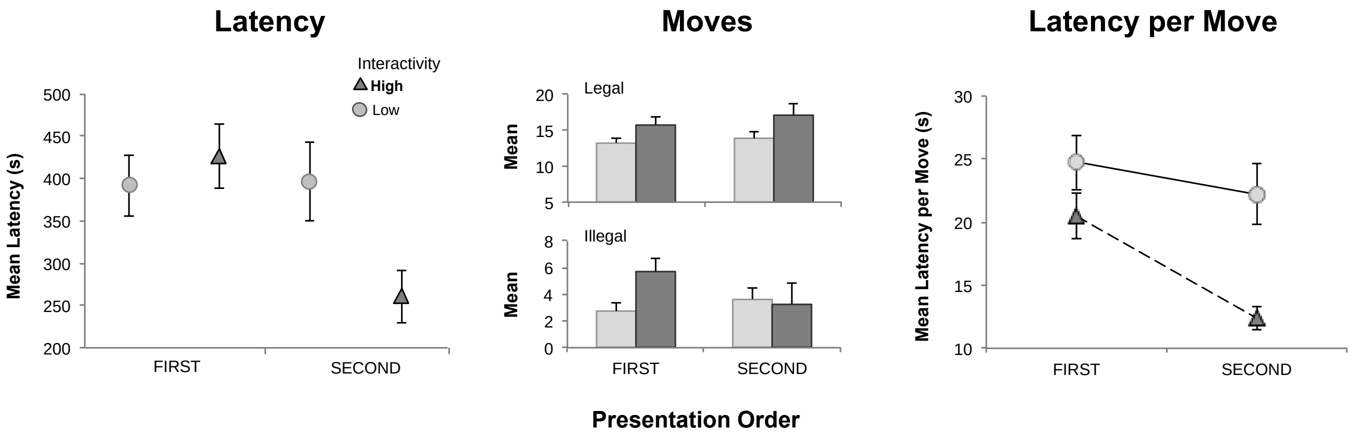

Figure 3: Mean latency to completion (left panel), mean number of legal and illegal moves (middle panel), mean latency per move (right panel) as a function of order (completed first or second) in the low interactivity (light grey) and high interactivity condition (dark grey). Error bars are standard errors of the mean.

The river crossing task was embedded in a testing session during which participants completed a number of other problem solving tasks unrelated to the present experiment. In the low interactivity version, the boxes on the first record sheet were completed with three C's and three W's on the left bank. Prior to the selection of a move, the researcher would draw an arrow above the raft to represent the direction in which it was travelling. The participants were discouraged from touching or pointing to the record sheet; they could not sketch out a move using pen and paper beforehand.

In the high interactivity condition, the board was placed on a table in front of the participant with the researcher placing all animals on the bank closest to the participant and positioning the raft on the river. This ensured all participants commenced the task with the same presentation. A move was defined as completed when whichever wolf (wolves) or chicken(s) being transported for that particular move were removed from the raft onto the other bank. Illegal moves were identified before they were completed, with animals and raft returned to the previous position on the board. In both conditions participants were given 15 minutes to complete the river crossing problem.

A 20-minute interval was designed between the two presentations of the river crossing problem during which participants completed a number of non-verbal puzzles, including finding similarities and differences between series of pictures, and identifying the odd picture in a series of thematically related pictures. Finally, the river crossing task was presented again in the alternate condition (either low or high interactivity) to that which was presented first; the order was counterbalanced across participants. Thus, the independent variables manipulated were condition (static, interactive) and order (static first, interactive first) in a 2×2 mixed design. Performance in both conditions was measured in terms of latency to solution, number of legal and illegal moves, and latency per move.

Results

Latency

Latencies to solution, displayed in the left panel of Figure 3, suggest that order had little effect on participants in the low interactivity condition but the problem was completed much quicker in the high interactivity condition when it was experienced second. A 2×2 mixed analysis of variance (ANOVA) revealed that the main effect of interactivity condition was not significant, $F(1, 49) = 2.14$, $p = .150$, while the main effect of order was significant $F(1, 49) = 4.20$, $p = .046$, as well as the condition by order interaction $F(1, 49) = 5.32$, $p = .025$. Post hoc tests indicated that latencies in the low interactivity condition did not decrease significantly from the first to the second presentation, $t(49) = 0.090$, $p = .929$. In turn, participants were quicker in the second than in the first presentation of the problem in the high interactivity condition, $t(49) = 3.744$, $p < .001$.

Moves

The mean number of legal and illegal moves are plotted in the middle panel of Figure 3. The high interactivity condition elicited a higher number of legal moves to solve the river crossing problem compared to the low interactivity condition and this was observed for both orders. In a 2×2 ANOVA the main effect of condition was significant $F(1, 49) = 11.63$, $p = .001$, while the main effect of order was not significant, $F < 1$, nor was the condition by order interaction, $F(1, 49) = 1.26$, $p = .267$.

In turn, the mean number of illegal moves was greater in the high interactivity condition when it was experienced first, but the frequency of illegal moves was relatively stable in the low interactivity condition across both presentations. In a 2X2 ANOVA the main effect of condition was significant, $F(1, 49) = 7.16$, $p = .010$, while the main effect of order was not significant, $F(1, 49) = 3.34$, $p = .074$ nor was the condition by order interaction, $F(1, 49) = 2.69$, $p = .108$.

Latency per Move

The latency per move data are shown in the right panel of Figure 3. Latency per move in the low interactivity condition was unaffected by order, however participants appeared faster at enacting moves in the high interactivity condition, especially the second time the participants engaged with the task. In a 2×2 mixed ANOVA the main effect of condition was significant, $F(1, 49) = 20.0$, $p < .001$, but the main effect of order was not, $F(1, 49) = 2.33$, $p = .133$; the condition by order interaction was significant $F(1, 49) = 11.4$, $p < .001$. Post hoc tests revealed that the mean latency per move in the low interactivity condition did not decrease significantly from the first to the second presentation, $t(49) = 0.858$, $p = .395$; in turn moves were selected faster in the high interactivity condition when that condition was experienced second, $t(49) = 4.60$, $p < .001$.

Discussion

This experiment investigated the impact of interactivity on problem solving performance for a river crossing problem. All participants were required to solve the problem twice, once in a low interactivity context in which move selection could only be simulated mentally and once in a high interactivity context where moves could be implemented in the world with a three-dimensional manipulable presentation of the problem. The repeated measures design eliminated random variance arising from between-subjects differences: Any performance improvement emerging in the high interactivity condition could not be attributed to a different group of participants with a differing pool of internal resources.

A high level of interactivity encouraged participants to make more moves in reaching a solution than when they completed the problem in the low interactivity condition; however, the order in which participants completed the task had no effect on the number of moves. In turn, the order in which the conditions was experienced had an effect on latency to solution. More important still, the main effect of order was qualified by a significant interaction: solution latencies in the low interactivity condition were similar whether this was completed first or second, while latencies dropped substantially when the high interactivity condition was experienced second. The latency per move data indicated that participants were always quicker to select a move in the high interactivity condition, and were generally quicker to select a move during the second presentation of the problem. However, the more important pattern in these data was the condition by order interaction: Latency per move dropped precipitously when the second presentation of the problem occurred in the interactive condition.

As Kirsh (2010, p. 442) puts it: “Cognitive processes flow to wherever it is cheaper to perform them”. Moves were cheap in the high interactivity condition — it is easier to move the pieces in the world than to simulate their movement in the head. More moves were made when the participants were given the freedom to transport the artefacts around the board to reach the solution than when moves were simulated mentally.

Learning Manifest Through Interactivity

The second presentation of the problem offered the opportunity to gauge the degree of learning and transfer. There was much evidence of learning, when the second opportunity to solve the problem took place in a context that favoured a high level of interactivity: Participants completed the problem in less time and selected moves at a faster rate than when the second presentation of the problem was in the low interactivity condition. In fact, when the low interactivity condition was experienced second, performance reflected little learning and transfer. This pattern of results suggests two competing explanations: (i) the process and quality of knowledge acquisition is different as a function of the level of interactivity or (ii) interactivity is a performance facilitator and a high level of interactivity more clearly showcases learning. Let’s take each in turn.

First exposure to the problem without much interactivity might have fostered the acquisition of a sounder and more actionable representation of the task and appreciation of an efficient sequence of moves to solution. In contrast, experiencing the problem in a context that fosters a high level of interactivity might not be accompanied by the same investment in cognitive effort, proceeding primarily on the basis of procedural learning, which in turn might interfere with the development of an accessible and transferable conceptual representation of the problem. As a result, when the problem is encountered for the second time in a condition without much interactivity, the procedural knowledge does not facilitate performance; however, when the second presentation occurs in the high interactivity condition, performance substantially benefits from the knowledge acquired on the basis of the experience in the low interactivity condition.

Alternatively, the substantial improvement in the high interactivity condition when participants are presented the problem a second time might not reflect differences in the type and quality of experience but rather release from a performance bottleneck. In other words, interactivity is a performance facilitator. Cognitive efforts and task demands are more exacting with low interactivity—as evidenced by the significantly longer latency per move. When participants encounter the problem a second time but this time can indulge in cheaper move selection by moving artefacts on the board, they experience a release from the cognitive demands of the low interactivity condition and are quicker at producing moves.

The moves data offer some support for the performance facilitating interpretation. The number of legal moves to completion increased from an average of 15.8 when the high interactivity condition was experienced first to 17.2 when it was experienced second. And while this was not a significant increase, the pattern suggests that participants did not acquire an appreciation of a more efficient path to solution—which would lead to the selection of fewer moves—on the basis of their experience with the low interactivity condition. The release from the cognitively demanding experience with the low interactivity condition coupled with familiarity with the problem lead participants to select more moves, and interactivity enabled them to do so quickly. Moves provide information, and as participants produced more moves, they were able to reach the goal state faster.

A higher level of interactivity led to improved performance in the river-crossing problem, when preceded with the experience of solving the problem in a context that did not afford the physical manipulation of the problem presentation. Learning from previous experience with the problem, coupled with the reduction in the mental cost of making moves through interactivity provided the solver with the freedom to experiment with more moves. Through the interaction with artefacts, individuals were provided with the opportunity to extend the process of thinking beyond the mind and into the physical world. These data underscore the importance of pursuing a program of research that explicitly contrasts performance when participants can manipulate a physical problem presentation and when they cannot. In addition, we would argue that such research efforts offer a more representative window onto problem solving behavior observed outside the psychologist's laboratory.

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