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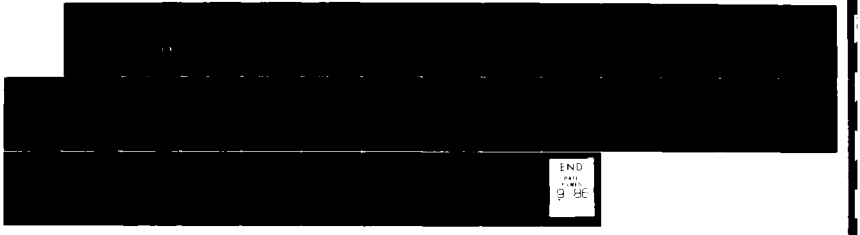

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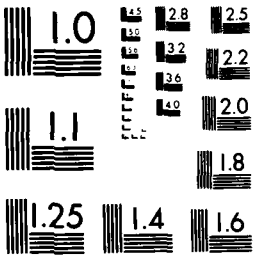

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FLEXIBILITY IN JOINT PROBLEM SOLVING

The effects of different points of view on overcoming blocks

Final Report

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Abstract

What are the factors that cause a problem solver to become blocked? And what are the factors that allow a person to become unblocked? These are the motivating questions for a set of studies we conducted of individual and joint problem solving. By constructing an isomorph of the classic "water jar" problems (Luchins, 1942) as a dynamic graphic microworld, we were able to identify several factors involved in producing blocked states. By comparing the behavior of individuals tackling the "missionaries and cannibals" problem to pairs of people solving this problem, we have been able to identify ways in which problem solvers operating in a social context are able to overcome problem solving blocks that are difficult for individuals. These studies point to the importance of "reflection" (evaluation of problem solving results) for flexible problem solving. These results may also account for the difficulty in showing learning in "discovery learning" uses of computers, such as the use of Logo, since such uses also often do not encourage students to reflect on the outcome of their problem solving.

Introduction

Recent research on the differences between expert and novice problem solvers has pointed to the importance of having many different ways of thinking about a task. Experts approach problems at a "global" level, and then adopt progressively more "local" levels of organization until they can solve the problem. Novices who have only the most specific way of thinking about the problem get lost in the morass of details. For example, in physics

problem solving, novices start writing down equations, while experts classify the problems and/or draw diagrams before writing down any equation (Larkin, McDermott, Simon & Simon, 1980, Chi, Feltovich & Glaser, 1981).

Problem solvers can also differ in the "angle" they take on a problem. For example, Hutchins & Levin (1981) found that subjects solving a river crossing problem mentally placed themselves in the problem, either on one or the other side of the river. Subjects changed their placement during the course of the problem. This placement, their conceptual "point of view," affected the kinds of mistakes that problems solvers made. Point of view has been found to be important in other areas of human cognitive functioning. Abelson (1975) showed that point of view affected subjects' recall of stories. Black, Turner & Bower (1979) found that point of view played a significant role in narrative comprehension, memory and production. Miyake (1986) found that point of view is critical for cooperative problem solving.

We carried out three sets of experiments aimed at exploring point of view, flexibility, and cooperation in problem solving: (1) Missionaries and Cannibals: Point of view in solitary and cooperative problem solving, (2) Zapworld: flexibility in computer problem solving environments, (3) Air Traffic Controller: Social resources in problem solving with in computer environments.

Missionaries and Cannibals: Point of View in Problem Solving

Our first set of experiments was directed at exploring the relationship

between point of view adopted by a single problem solver contrasted with the point of view adopted by pairs of problem solvers. The subjects were presented a river crossing problem involving missionaries and cannibals represented in a three-dimensional display to be manipulated. We confirmed the early work of Hutchins and Levin (1981) that the point of view taken affected the kinds of errors that solitary subjects made. In addition, we found that pairs of subjects approached the problem in very different ways than subjects working alone.

The presence of a second problem solver increased the amount of reflection on past moves and planning for future moves. Novices working together began to assess problems in a global way that is more characteristic of expert problem solvers (Larkin et al., 1980). The cooperative situation led to much quicker and more systematic solutions to the problem.

Zapworld: flexibility in computer problem solving environments

The second set of experiments we conducted suggests that problem reflection may be a critical factor in flexibility of problem solving. We created a computer isomorph, "Zapworld," to the classic War Jar experiment of Luchins (1942). When students approached either the Water Jar problems or our "Zapworld" problems on paper, they did not try to determine what type of problem they were approaching; instead they moved immediately to the solution. Once they found a "formula" they applied it automatically and therefore became blind to problems that could be solved in a straightforward manner. Subjects who blocked on the water jar experiment were very similar to novice problem solvers in physics that began with the formula rather than assessing the type of problem they were confronting (Larkin et al., 1980).

We found differences in the performance of subjects on the computer isomorph. First, when faced with the computer version of the problem, subjects were more likely to move to a trial and error approach. The visual properties of the problems made them less likely to search for and apply a formula. They were less likely to be blocked by a shift in problem type, which seems to be because they approached each problem as a new one.

We modified the procedure making it necessary for subjects to reflect on how they had solved a previous problem. The requirement that subjects report on their behavior increased their monitoring behavior. Increased monitoring and reflection on problem solving strategies led to flexibility in approaching new problems. The subjects in this reflective condition avoided the blocked state that occurred when the same set of problems was is worked with pencil and and paper. These findings regarding the critical role of monitoring in problem solving shed some light on the issue of how computers can be used as effective tools in improving problem solving skills.

Air Traffic Controller: Social Resources in Computer Problem Solving

Two of our sets of experiments suggest that cooperative arrangements are effective in improving problem solving because it increases the need for reflection on past actions and planning. The last set of experiments was aimed at exploring the role of social resources in problem reflection and monitoring.

The Air Traffic Controller experiments situated cooperative problem

solving (as in the missionaries and cannibals experiments) in a computer environment (as in Zapworld experiments) in which the subjects had to work together to solve a set of problems. In some of the conditions, the role of problem reflection was systematically assigned to a monitor. In other conditions, the subjects were to divide up the task themselves. The most effective way of dividing up the task was for one of the subjects to take responsibility for the actions and the other subject to monitor the behavior redirecting the problem solving resources of the team when it became appropriate. This manner of dividing up the task enabled the person acting to take a more local point of view while the monitor maintained a global point of view. These findings confirmed the important role of problem monitoring, reflection and point of view in problem solving. They point to social resources as a possible way to integrate problem monitoring and reflection into complex problem solving environments.

Implications: A Demand Driven Expert System

The research in this project points to the value of social resources in problem solving. Flexibility in problem solving was increased in situations in which the problem solver reflected on or monitored past behavior and used this information to plan future moves. When two problem solvers worked together on a problem, particularly when one problem solver took on the task of monitoring the progress, the pair was able to move to solutions in a more efficient way than subjects were able to accomplish on their own.

A dynamic "demand driven" expert system that utilizes a network of social resources is recommended for problem solving based on this research. In the common approach to expert systems, the domain expert and the

programmer face the "problem" of creating the system and determining the conditions of it use before it is made available to those who will interact with it. They will need to determine what type of information should be provided, how it should be accessed by the novice and how the computer will deal with questions that go beyond the resources provided.

We recommend another approach to the design of expert systems which is to use computer resources in concert with human or social resources. In this demand driven system, the computer could be used as a powerful tool by experts in diverting routine questions to previously generated replies. By maintaining a human interface with the system, the non routine questions can be handled by the flexible skill of the expert. Such a system could be made more automatic in areas which the the expert assessed as able to provide reasonable information to most of the inquires. This demand driven expert system would enable many people to receive fast and efficient computer help with an one line expert ready to respond when the computer fails to generate an acceptable response. By combining computer and human resources in a social network, many people can receive routine responses to common problems with the assurance that the unusual problems will get the interpretive work of a human expert.

THE MISSIONARIES AND CANNIBALS PROBLEM: POINT OF VIEW IN PROBLEM SOLVING

Studies of peer learning suggest that there may be benefits which accrue to people working together that do not accrue to individuals working

alone. Vygotsky (1978) discusses learning situations in which more knowledgeable people assist less knowledgeable people until the less capable are able to take over the task. In this way of thinking, knowledge proceeds from the social to the psychological, as individual learners internalize the teachings from representatives of the larger society.

Observers of students teaching students (Steinberg & Cazden, 1979; Mehan & Riel, 1982; Riel, 1982; Mehan, Moll & Riel, 1985) find that peers make suggestions, model and demonstrate activities to each other. Studies of "cooperative learning" situations (Slavin, 1980; Webb, 1982; Kagan, 1985) in which students work together in teams demonstrate that students improve in academic achievement, as well as in social relationships.

Verbal interaction is a potentially important mechanism in these situations, because students working together talk outloud to each other. The act of verbalizing material is thought to lead to cognitive restructuring on the part of the students who are attempting to explain different points of view, which in turn, can lead to cognitive conflicts. Cognitive conflicts are important, it has been argued, because it forces learners to examine their own understanding, and to seek resolutions of conflicting point of views (Piaget, 1971).

Creativity in problem solving is often the result of a great deal of knowledge in a given domain and the ability to suspend that knowledge and look someplace else for a solution. Being able to take an unconventional point of view towards a knowledge base may be a general problem solving strategy that leads to new solutions. How does a person use knowledge in a productive, strategic way and at the same time become free to view the

problem in a fresh or new way? We arranged for problem solvers to reflect on or evaluate their problem solving strategies by putting them in a social situation in which they had to convince one another that a given move or strategy was the best one.

The Problem

"There are three missionaries and three cannibals on one side of the river and your task is to get them across the river using a two person boat without ever letting the cannibals outnumber the missionaries on a side of the river." These are the instructions given to subjects in the "Missionaries and Cannibals" problem commonly used in cognitive research (Ernst & Newell, 1969; Reed, Ernst, & Banerji, 1974; Jeffries, Polson, Razran, & Atwood, 1977; Hutchins & Levin, 1981). The solution to the problem involves a sequence of eleven steps from initial state to conclusion. The sequence is difficult to see immediately and before finding the solution, subjects often make illegal moves and other legal but unproductive moves.

We used the Missionaries and Cannibals problem to explore point of view in problem solving because (a) it is a problem situation in which there are a number of necessary moves toward a solution which can be coded, (b) it is a problem that is relatively difficult to solve in which individuals often express feelings of being blocked, and (c) subjects talk about their behavior in a way that often makes it possible to identify the point of view they have adopted in solving the problem.

Procedures

We had subjects solve this problem in two different conditions. The first is the more standard situation in which a single person manipulates objects that represent the problem while "talking aloud" about the steps of problem solving. The verbal protocol often relates what the problem solver is doing, but not why. The plans and strategies remain difficult to infer from the verbal report.

In the second condition, two people were asked to work together to solve the problem. When people solve problems in social settings, they often discuss their plans or reflect on the success of previous actions (Miyake, 1986; Martin, 1983). The need for coordinated action and division of labor often leads to shifting responsibility for monitoring and evaluating each action taken by the pair.

We wanted to see what happened when two players with either the same or different points of view worked together in this problem environment. Previous research (Miyake, 1986) suggests that subjects with different points of view are slower to agree on an action to take in solving a problem, but they are blocked less often. Pairs of subjects with a consistent point of view should be as fast or faster than an individual, but the pair might have even a harder time overcoming a block than an individual subject because they will reinforce their support for the same approach, perhaps making it harder to switch to a more productive strategy.

We had 10 individuals and 10 pairs of subjects solve the problem. All

sessions were audiotaped with an experimenter taking notes about behavior not available from the tape. The notes and the audiotape were used to construct a verbal transcript and a problem solving transcript. The verbal transcripts showed all the speech acts of the subjects, the problem solving transcripts listed all moves either made or considered from the initial state through the eleven steps necessary for the solution of the problem. We used the information in these transcripts to compare the solitary sessions with that of the pairs.

Results

Point of View. It is not always possible to identify the point of view of the person in both the individual and the joint sessions. Usually the initial point of view is evident in the way the person talks about the the game pieces, but the shifts in point of view are not always well marked. It was much easier to determine point of view in the individual subjects' descriptive monologues than it was in the joint dialogs produced by the pairs of subjects. The individual subjects were much more likely to detect an error they made before going on to a new move when the error occurred on the same side as their point of view, and were much less likely to do so when the error was on the other side of the river (Table 1).

	Near side errors	Far side errors
Detected by the subject	12	4
Undetected	2	7

Table 1: Errors made by the individual subjects (n=10).

Another clue that a shift in point of view often helped a subject overcome a blocked state comes from a subject who began the problem by locating herself on the beginning side of the river with the Missionaries and Cannibals. She continued to "move over" or "take over" Missionaries and Cannibals and "bring them back" to the beginning side of the river. After much difficulty she saw the solution. As soon as she began to describe it, it became clear that she had shifted her point of view to the goal side of the river. She began to talk about "bringing over" Missionaries and Cannibals to the goal side and "taking them back" to the initial side. We suspect that her shift in perspective helped her see the problem in a different way, thereby making the solution more salient.

It was more difficult to determine the point of view of the pairs of subjects because their talk was less descriptive and more focussed on *planning and negotiating* the next move. There was a sense of shared point of view in that the subjects often used the same vocabulary to describe their moves but it was too difficult to use this data to track their point of view.

At the outset, we assumed that a similar point of view might lead to a blocked state as the subjects would both be viewing the problem in the same way, validating rather than providing a different perspective. However, this did not happen. Commonly one person took control over making the moves either by describing them or more often by controlling of the game pieces. This state of affairs (one person maintained control with the other person monitoring) continued as long as they continued to make moves that made progress toward a solution of the problem. If illegal or repeat moves were

made, it provided the other player with the opportunity to take control of the game pieces or to provide a different approach to the solution. At these times, the other subject contributed to the "group process" by suggesting alternative moves.

Comparison of solitary and joint problem solving. There was a very different pattern of behavior when a pair of subjects solved the Missionaries and Cannibals problem than when individual subjects worked alone (see Table 2). On the average, the single subjects took twice as long, (14.56 minutes for single subjects and 6.63 minutes for pairs), and made more moves (27 to 17) with a higher percentage of both illegal (12% to 8%) and of repeat (40% to 22%) moves. The pairs were also better at detecting their own illegal moves or errors. This contrasts with the performance of single subjects who often would continue after a illegal move making it necessary for the experimenter to point out the illegal move.

CONDITION	TIME mins.	TOTAL MOVES number	ILLEGAL MOVES number	%	REPEAT MOVES number	%
Single Subject n=10	14.56	27.0	3.2	12%	12.9	40%
Pairs of Subjects n=10	6.63	17.1	1.5	8%	4.6	22%

Table 2: Comparison of single subjects with pairs of subjects solving the missionary and cannibals problems

The single subjects approached the problem by first moving the pieces directly without evaluating the possible alternative moves. Their verbal reports most often described their actions and less often described a plan for solving the problem. Single subjects rarely proposed a possible move,

considered it and then after this evaluation decided either to make or not make the move. Instead, single subjects made moves without any evidence of a plan that extended beyond the next move into as overall plan for solving the problem. The single subjects often expressed a sense of frustration as they continued to repeat a high proportion of their moves. When they found themselves blocked--making the same moves or illegal moves over and over again--they were less likely to begin the problem over. Consequently, when they did solve the problem it was in a piecemeal fashion. That is, they moved from initial state to the midpoint and then after a number of illegal and repeat moves, they worked through the middle steps to the end of the problem. Both the verbal and problem solving transcripts indicate that many of the single subjects solved the problem through a trial and error exploratory pattern rather than by a search for an understanding of the sequence of moves which lead to the final solution.

Pairs of subjects working together on the Missionaries and Cannibals problem were able to solve the problem much faster than subjects working alone. In both experimental conditions, the subjects talked about the moves that they were making but the function of the talk was very different in the two situations, however. In the single subject condition, subjects provided a verbal account of their actions. There was less evidence of analysis or planning of moves in the verbal transcripts. The pairs of subjects used verbal interaction as a means for reaching agreement about what the best next move in the problem would be. This negotiating and planning seemed to be productive or subjects to find efficient solutions to problems. The need to justify a move often led to reflection on a given move and an analysis on how it is likely to bring the problem solvers closer to the goal state. The

second person also served as an evaluator noting illegal moves and the lack of progress of a given approach. In the cases when pairs of subjects found themselves having difficulty at a particular step in the problem, they were more likely to reset the problem and trace the whole sequence of steps. This contrasted to the behavior of the single subjects who continued to look for a move that would lead them to the end.

The relative ease at which pairs of subjects solved the problem compared to single subjects suggests that the interaction between the players was an important resource for problem solving.

ZAPWORLD: FLEXIBILITY IN COMPUTER PROBLEM SOLVING ENVIRONMENTS

When cognitive theorists and educators examine problem solving, they have generally focussed on the initial steps in the problem solving process: problem definition, alternative paths possible to the solution, and the possible problems that arise when people "fail" to discover the relatively easy solution.

There is, however, an important part of problem solving that is less often described in cognitive and educational research: problem solvers' reflection upon or evaluation of the solution that was found. Was it the best possible solution? The only solution? How was it discovered? Could it be repeated? What justification can the problem solver offer for his or her move?

We often solve problems by looking for the most immediate solution with

little concern for other ways that we could have solved the problem (Simon, 1969). If similar problems are unlikely to appear, this method may be appropriate. For problems that do reoccur, however, skilled problem solvers will be those who have a deeper understanding of the fit between the present problem and a range of problem solving strategies.

Our initial work with the Missionaries and Cannibals problem pointed to the vital role that monitoring and reflecting play in problem solving domains. The second set of experiments are based on the Luchins Water Jar Experiment in which subjects adopt a strategy based on a small set of problems that blinds them to the possibility of a more direct and simple strategy (Luchins, 1942). We continued to explore the role of reflection in helping subjects break out of the conventional point of view in order to find solutions to problems.

The Problems:

We implemented an isomorph of the water jar experiments in InterLISP on the Xerox 1108. In this computer version, "Zapworld," the subject is presented with a number of moving objects each with a certain amount of charge. The goal is to accumulate a specified amount of charge by gaining charge from charged objects (by touching them with the mouse and pushing a mouse button) and by losing charge to uncharged objects.

We used the original problem set from Luchins (1942) which included 11 problems with two sets of "critical" problems (see Table 3). The first example problem and the next five problems can all be solved by using a

particular lengthy procedure. The next two problems (called critical 1 and 2) can be solved by the same lengthy procedure or by a shorter "direct-method" strategy. The 10th or "direct-method problem" can only be solved by the shorter strategy. Then two more problem (critical 3 and 4) were given in which either the long or direct method strategy could be used.

		Elements			Goal	Problem Type
	1.	29	3		20	Example
	2.	21	127	3	100	A
	3.	14	163	25	99	A
	4.	18	43	10	5	A
	5.	9	42	6	21	A
	6.	20	59	4	31	A
Critical 1:	7.	23	49	3	20	A,D
Critical 2:	8.	15	39	3	18	A,D1
Direct	9.	28	76	3	25	D
Critical 3:	10.	18	48	4	22	A,D1
Critical 4:	11.	14	36	8	6	A,D

Table 3: Original problem sequence used in the Luchins Water Jar experiment (Luchins, 1942).

There are 4 steps to the long solution required to solve an A type problem: (1) begin by selecting a large charged particle, (2) discharge partial charge into an uncharged middle size particle, (3) discharge partial charge into the smallest size uncharged particle, and (4) repeat the third step. There are 2 steps required for the direct method solution for D problems: (1) Select a middle sized charged particle, and (2) discharge part of the charge into a small uncharged particle. There are also just two steps associated with the solution to direct D1 problems: (1) select a middle sized particle, and (2) select a small charged particle.

In the classic experiments by Luchins, only 19% of the subjects saw and utilized a direct method for solving the first set of critical problems. Many of them took much longer to solve a direct method problem and only 39%

made the shift to a direct method of solution for the last two critical problems.

Procedure:

College students worked the problem sets on the computer using a mouse to control the particles. An initial example was added to the problem set to demonstrate how the mouse operated. The instructions were similar to the ones used by Luchins. The computer kept a history of the moves that were made by the subjects and the time for each move. The experimenter kept notes on the verbal comments and any planning or descriptions of the problems. After the first set of problems these procedures were modified to further explore the findings. These modification and their results are described in the following section.

Results:

We found a surprising result when subjects worked the Luchins problems in computer environment of Zapworld. The subjects did not get blocked on the "critical problems" in the same way as Luchins' findings would predict. When faced with the first set of critical problems, a much lower number of subjects were blocked, with more than half (63%) shifting to the direct method immediately, compared to less than one fifth in Luchins' experiments. After confronting the "direct-method" problem, most of subjects (85%) shifted to the direct method for the last two critical problems (Table 4).

Problem Set	n	C1 & C2	C3 & C4
Luchins: Water Jars	79	19%	39%
ZapWorld: Computer	20	63%	85%

Table 4: The percentage of subjects who used the direct solution to solve the two sets of critical problems in the Water Jar experiments (Luchins, 1942) and in the ZapWorld isomorph.

We next explored why subjects did not seem to get blocked in the computer version of the task, considering both the problem isomorph and new computer environment as factors in this finding. We used computer printouts of the problem to create a pencil and paper version of the task. The initial screenful for each of the problems was printed and stapled together. Subjects in this new paper and pencil version of the task were given the same instructions as the subjects in the original computer version of the task.

Subjects' performance in this paper and pencil version of the Zapworld isomorph replicated Luchins' findings. Subjects were blocked in this format in a way that was similar to that found by Luchins, although the finding was not quite as strong as he reported. When they reached the first set of critical problems, 41% shifted to the direct method and 55% shifted to the direct method for the last two problems.

To explore the differences between working the same problems with paper and pencil and with the mouse on the computer, we compared the strategies that were used by the subjects as they worked the problems. It appears as if solving the problem on paper did not allow the subjects the opportunity to make intuitive guesses which might lead to the solution of a problem. Instead, subjects working with a pencil developed and applied the lengthy

problem solving algorithm that worked for the beginning problems. Once this procedure was developed, they continued to use it until they found that it did not work. They were more likely to use the longer procedure over the direct method even after encountering a problem that indicated that the procedure might not work in all cases. The paper and pencil subjects seemed to approach the problem in exactly the way one would predict from the original Luchins data.

By contrast, the computer implementation of the problems seemed to have focussed subjects' attention on visual cues, and at the same time weakened their memory for and automatic implementation of previously successful strategies. The representation of the problem on the computer enabled the subjects to explore the problem visually and not necessarily attend to the computations which was the only strategy available to the person working the problem with paper. The behavior of the subjects on the computer was similar to that which we had seen in the single subjects approach to the Missionaries and Cannibals problem. They could try things out by interacting with the problem and using visual cues to suggest the next action. The subjects tried a number of different strategies with each problem and one subject even discovered a new solution to the "direct-method" problem when working on the computer. Another subject was about to use the strategy that had been successful in the past but he made an error in discharging to the wrong particle. The new state created on the computer by this error suggested the direct method of solving the problem.

The variation in the time that subjects working on the computer took to find a solution for each of the problems did not suggest that they were

developing a systemic problem solving procedure. If each problem was being taken as a new problem, then it would not be surprising that they would discover the more direct method of solving the critical problems.

Since our experiments with the Missionaries and Cannibals problem had pointed to the role of evaluation or reflection in problem solving, we decided to try a change in the procedure that would encourage the computer subjects to reflect on their problem solving approach. The Zapworld computer procedures were modified so that after each solved problem, the subjects had to record how they had solved the problem before moving to the next problem.

This new condition, which required the subjects to reflect on the strategies they were using, had the expected result of making it more likely that they would be blocked on the first set of critical problems. The subjects continued to use the "A" solution when it was no longer the most efficient solution. In fact, their performance on the first set of critical problems indicated that they were even more likely to be blocked than the subjects who worked the problems on paper. On this first set of critical problems, 70% of the subjects continued to use the long procedure (Table 5).

Problem Set	n	C1 & C2	C3 & C4
Luchins: Water Jars	79	19%	39%
ZapWorld: Computer	20	63%	85%
ZapWorld: Paper/pencil	11	41%	55%
ZapWorld: Computer with Recorded Solutions	5	30%	90%

Table 5: Comparison of the the percent of subjects who used the direct solution to solve the two sets of critical problems in the Water Jar experiments (Luchins, 1942) and in three conditions in the ZapWorld isomorph.

Again, we found a surprising result when subjects were asked to reflect on the problem solving by recording their solution. Almost all the subjects, (95%), shifted to the short strategy for solving the second set of critical problems. The performance on the first set of critical problems indicates that they had established a problem solving strategy. They continued to use the 4-step "A" solution for these critical problems failing to notice the direct "D" approach. But following the problem in which the "A" solution was not effective, they were able to reassess the problem and discover the new direct method reasonable quickly. When the second set of critical problems appeared, they were immediately able to solve the problems by means of the direct solution. Unlike the tendency of earlier subjects (who continued to apply the strategy that had worked in all but the last problem), these subjects seemed ready to add the new 2 step "D" solution as a alternate approach for solving subsequent problems.

The combination of working in a visual representation of the problem (which encouraged a discovery approach to the problems) with a condition in which the subject must reflect back on the problem led to the greatest flexibility in problem-solving. This finding suggests that reflection on the problem solving strategies resulted in a clearer development of a problem solving procedure that is applied for efficiency. But once that strategy is shown as not always effective, the subjects seemed to immediately return to assessing the problem prior to implementation of a strategy.

Implications for Computer-Based Problem Solving Instruction

In both the Missionaries and Cannibals and the Zapworld problems we

found that reflection on the moves that were necessary for finding the solution led to better problem solving. In Missionaries and Cannibals, the subjects who worked cooperatively were placed in a situation in which they had to negotiate their moves. The cooperative condition made is necessary for the subjects to explain why a given move was likely to bring them closer to the solution of the problem.

In the Water Jars isomorph, Zapworld, we made it a condition of the task that the subjects stop and explain how they has arrived at the solution of a problem. This reflection or evaluation of the solution helped focus the attention of the subjects on a productive strategy. Unlike the subjects in the classic Luchins experiments or the subjects who did the exact same task on paper, the subjects who reflected on the problem solution were able to shift to a new "direct-method" problem solving procedure with no difficulties.

These findings suggest why problem solving environments on the computer often allow students to do what looks like sophisticated problem solving but it is difficult to find any transfer of the problem to tasks done off the computer. The research on Logo as a way to teach problem solving has produced disappointing results (Papert, Watt, diSessa, & Weir, 1979; Pea & Kurland, 1984). Inducing students to reflect on what they have learned and searching for other ways to accomplish their goals might be a productive way to extend the power of this learning environment. Our research suggests that interaction with the computer in such a setting might be more effective if there is a reflective stage in which students review what they have done on the computer and why.

AIR TRAFFIC CONTROLLERS: COOPERATIVE DIVISION OF LABOR

The first two phases of our research has focussed our attention on the important step of evaluation in problem solving. We continued to explore aspects of problem solving instruction that help students learn how to analyze what they have done as well as helping them develop flexibility in using a new approach when blocked. Through a series of studies of experts and novices jointly working together in a simulated air traffic controller microworld, we have been able to identify some of the factors involved in the effective coordination in efficient problem solving. These studies varied the division of labor of pairs of subjects issuing commands to multiple airplanes entering and leaving a specified airspace. The discourse between experts jointly tackling this task reveals the ways that experts coordinate their talk and action to do the task and simultaneously to monitor each other's performance on the task.

How do people work cooperatively in complex tasks to solve problems? In order to address this question, we studied both experts and novices operating a simulation of an air traffic controllers' task. We had pairs of subjects who were simultaneously operating a microcomputer-based program issue commands that directed simulated airplanes to enter and leave, takeoff and land in a simulated airspace displayed on the microcomputer's video display.

In previous research Miyake (1986) found that in a two-person joint problem-solving situation, subjects frequently divided their roles

so that one did the task while the other monitored the actions. This manner of dividing the task frequently promoted constructive interaction.

The division of the task according to roles (task-doer and task-monitor) is different than the division of the task into parts (with each participant taking responsibility for an assigned subpart of the task). It was a goal of these experiments to analyze further how these two different types of task division differ in detail and in consequence.

The Problem:

The problem domain in these experiments is a set of airplanes that were generated by the computer. The planes would need to be guided through air corridors to their predetermined goal. Planes appear in a three dimensional grid with requests to land or take off from one of two airports or to fly through the airspace. The air traffic controller is responsible for guiding the course of all planes. The amount of time available to handle a fixed number of planes determines the level of difficulty. If the air traffic controller allows to airplanes to come too close to each other or misdirects a plane, then the session is ended.

Two keyboards were wired into a single microcomputer so that each subject could have equal access to the key entry. Each keyboard had a built-in buffer which held keystrokes command until the Return key was pressed.

The Procedure:

There were three sets of experiments in this phase of our research. In the first set of experiments, two expert air traffic controllers, El

and E2, worked cooperatively in nine sessions each with a different form of division of the task.

Each of the subjects was placed in the three task monitor positions while the other was the task doer. They participated together in the subtask division taking on the assigned task. All sessions in this set were played at the level of 40 "minutes" to handle 26 planes. This was a more difficult level than either of the two subjects were able to achieve prior to the experiment.

In the second set of experiments, the experts, E1 and E2 were matched with a novice for a total of 3 sessions for each pair. A novice was defined as someone who understood the aim and the procedure of the simulation, but who had not worked through the simulation more than once. The expert always assumed the role of task-doer and the novice was placed in each of the three conditions described above.

In the third set of experiments, two novices were placed together in three sessions. Before the experiment, they were asked to talk about the best way of dividing the task. They were permitted to divide up the task in whatever way they wished.

Results

The average numbers of planes successfully controlled in the different types of problem session are shown in Table 5.

	Player-monitor division		Simple partition	
Expert & Expert	n=6	11.5	n=3	6.0
Expert & Novice	n=6	22.7		---
Novice & Novice	n=1	6.0	n=2	3.5

Table 6: Average number of planes successfully controlled in Air Traffic Controller.

Expert & Expert Problem Solving. It is apparent for Table 6 that experts performed better when they divided the roles rather than partitioned the task. There could be several explanations for this finding: 1) the monitor frees up some resources of the task performer; 2) the monitor provides a wider perspective, particularly when the doer focuses narrowly on one portion of the task; and 3) the problem session is closer to individual sessions, in which each participant has practiced extensively.

Expert & Novice Problem Solving. It is also clear from Table 6 that novices can profitably serve in the role of monitor. While readily admitting the paucity of our data, this result seems to suggest that sharing the goal and having a wider perspective are two possible sources of the power of a monitor. Reasons for this observation could be: 1) the monitor can provide a wider perspective, 2) the expert's explanation to the novice helps the player himself make his plans explicit and remember them better, 3) social facilitation effects such as higher motivation, expectation, or attention to an audience result in more careful attention, and 4) the monitor frees up some of the cognitive resources of the task-doer.

While the fourth reason is a possibility, it is weak. There were clearly cases in which the cognitive load was heavier because the player had to explain some basic movements. Notice the novices here were at least

familiar with the task, or at least with the goal of the task. A person who does not know anything might be a burden on the expert. If this were the case, it would rule out a simple social facilitation argument.

Novice & Novice Problem Solving. In a discussion before starting the simulation, the novice pair decided that a simple partition would work best for them. After that decision they worked through three problem sessions. At first they tried to implement their preferred strategy. Then a player-and-monitor problem session, and another simple partition problem session was implemented. The results indicate that in this try-out they performed better when they divided the roles. Interview with the subjects after the experiment was concluded revealed, however, they preferred to play in a partitioned condition, saying that they could concentrate more when the task was smaller.

A Micro-Analysis of problem sessions.

In order to look at the process of joint problem solving in more detail, we transcribed the verbal interaction between pairs while problem solving and analyzed the relation between the speech acts of the participants and the actions taken in the simulated microworld.

The internal structure of problem sessions. The microworld interactions tend to have an episodic structure. Periods of little action on the part of the participants are separated by periodic "crises," periods of intense action. We developed a measure which captures this episodic

nature: we graphed the number of commands issued by the participants over time; peaks of high frequency actions mark the crisis episodes.

A more detailed analysis of expert & expert pairs indicates that the distinction between monitor and doer can become blurred during a problem session. In some work sessions, there did appear to be a clear distinction between a task monitor and task doer, but in other sessions, participants either switched roles or assumed both simultaneously. The expert in this task was flexible depending on the situation.

During the course of a problem session, both participants conversed in order to coordinate moves, develop overall strategy, and keep each other appraised of moves issued and the status of the airplanes. We performed a detailed analysis of the speech acts in the discourse between joint problem solvers, using the classification system specified by D'Andrade and Wish (1985). This speech act analysis indicates that the number of speech acts issued over the course of a game is inversely related to the number of actions per unit time. As the number of action and monitor commands issued increased, total speech acts decreased. High cognitive load seemed to inhibit conversation. In these cases, an indirect effect of a crisis was to discoordinate participants, since they couldn't continue to communicate with each other. Along with this decrease in the number of overall speech acts, there was a corresponding decrease in talk about point of view, making it more difficult for the joint problem solvers to be aware of each other's point of view.

Implications: A Demand Driven Expert System Network

The results of the research on the Missionaries and Cannibals problems, Zapworld and the Air Traffic Controller task provide further support for the importance of external information resources for an expert to function well. Although this notion seems fairly straight-forward, it has some interesting and important implications for the design of "expert systems". Most of the existing expert systems are designed to operate in a "stand-alone" fashion, in isolation from any other information resources. If we take seriously the results of our studies of human experts and those of others (Suchman, 1985; Hutchins, 1986), we would build instead "expert system networks," embedding a computer-based expert program into a communication network so that it can draw upon other resources (human and computer-based). For such a system to utilize social resources, however, each "node" in the "expert system network" has to understand its own limitations.

To take this notion of an expert system network a step further, we have developed a very different methodology for the construction of machine-based expertise. We call this approach "demand driven," to distinguish it from the standard approach, which might be called "supply driven." Typically, a project to construct an expert system will hire an expert human, and then work with that expert to build into the system the knowledge supplied by the expert.

Let us consider instead a different approach, in which the expert human is part of an electronic network, with other humans drawing upon the expert's knowledge by sending electronic messages which the expert answers by writing electronic messages. After a number of exchanges, the expert will notice that there are certain high frequency questions that all require the same routine answer. These "routine" questions are now excellent candidates for information to embed in the computer component of the "expert system", because 1) they are likely to be drawn upon again, 2) since they are routine, they are likely to be easier to specify in a machine representation, and 3) they are likely to be relatively non-controversial. In contrast, the kinds of knowledge supplied by an expert when asked in the conventional approach are likely to be issues at the frontier of the expert's knowledge domain, which are likely to be in low demand by novices, hard to represent, and controversial (i.e., one expert's answer is unlikely to be the same as another's).

Following this methodology one more step, we can construct a "message assistant" program, based on the artificial intelligence techniques drawn upon by current expert systems, for storing these routine answers, which will scan the expert's incoming mail and try to identify incoming messages which match the pattern specified by the corresponding routine question. If there is a match, then an automatic response can be specified; if there is no match, then the incoming message is given to the human expert to answer. Gradually, over time, the human expert can give more and more routine answers to routine questions to his or her message assistant. In this way, the message assistant gradually increases its "expertise", incrementally becoming an expert system, but one which is fundamentally integrated into an expert system network with a dynamic human component.

We are currently pursuing this direction pointed to by the studies of experts functioning in a social environment.

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