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TNO-report IZF 1991 B-11
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HUMAN COGNITIVE PROCESSES IN
COMMAND AND CONTROL PLANNING.
3: DETERMINING BASIC PROCESSES
INVOLVED IN PLANNING IN TIME AND
SPACE

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*On scientific exchange from Defence and Civil Institute of Environmental
Medicine, P.O. Box 2000, North York, Ontario, Canada M3M 3B9

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Number of pages: 51

92 2 04 051

92-02900



Netherlands organization for
applied scientific research

TNO Defence Research consists of:
the TNO Physics and Electronics Laboratory,
the TNO Prins Maurits Laboratory and the
TNO Institute for Perception.



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Report No.: IZF 1991 B-11
Title: Human cognitive processes in Command and Control planning. 3: Determining basic processes involved in planning in time and space
Authors: C.A. McCann and drs. P.J.M.D. Essens
Institute: TNO Institute for Perception
Group: Cognitive Psychology
Date: August 1991
DO Assignment No.: B91-35
No. in Program of Work: 733.2

SUMMARY

↳ This study investigates how people create plans to accomplish a task that has both temporal and spatial components. The study had two goals: to develop a method for determining the cognitive processes associated with planning; and to develop a model for efficient planning for the task used in the study. Two planners gave verbal and graphical protocols while planning the most efficient way for shopping robots to pick up commodities in a grocery store. Each planner created a plan for twelve such problems and the plan was executed after each planning session. The protocols were analyzed to identify the primitive concepts and actions used in the planning process. Observations of planners' behavior in this study indicated that plans were developed in an evolutionary manner. Planners discovered and refined methods for organizing the information and procedures for manipulating it during the course of the sessions. Furthermore, it was shown that planners attended to different levels of detail of information in planning, and used a variety of planning strategies. A hierarchical model for efficient planning for this task is proposed that assumes plans are developed hierarchically at three successive levels of detail. ↵

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Cognitieve processen in Command and Control planning. 3: Basisprocessen in planning in tijd en ruimte

C.A. McCann en P.J.M.D. Essens

SAMENVATTING

In deze studie wordt onderzocht hoe mensen plannen creëren voor een taak die zowel temporele als spatiële componenten bevat. De studie had twee doelen: het ontwikkelen van een methode voor het bepalen van de cognitieve processen die met planning samenhangen en het ontwikkelen van een model voor efficiënte planning voor de taak gebruikt in deze studie. Twee planners gaven verbale en grafische protocollen terwijl ze een planning maakten voor de meest efficiënte weg voor winkel-robots om goederen op te halen in een winkel. Voor twaalf van deze planningsproblemen creëerde elke planner een plan en dit plan werd uitgevoerd na elke planningsessie. De protocollen werden geanalyseerd om de primitieve concepten en acties te identificeren die gebruikt werden tijdens het planningsproces. Geobserveerd werd dat plannen op evolutionaire wijze werden ontwikkeld. Tijdens het verloop van de sessies ontdekten en verfijnden planners methoden en procedures voor het organiseren en manipuleren van de informatie. Verder werd gevonden dat planners een verscheidenheid aan strategieën gebruikten en aandacht gaven aan verschillende niveaus van detail van informatie in de planning. Een hiërarchisch model voor efficiënte planning voor deze taak wordt gepresenteerd dat ervan uitgaat dat plannen hiërarchisch ontwikkeld worden op drie opeenvolgende niveaus van detail.

1 INTRODUCTION

The creation of plans concerning the use of resources to accomplish tasks in a spatial environment is paramount for successful command and control operations. Yet relatively little is known about how humans plan these kinds of tasks; there have been few empirical studies investigating this issue (McCann, 1990). This lack of fundamental knowledge about the cognitive processes used by people in creating plans to be executed in time and space must be addressed if we are to be successful in building computer-based systems for assisting military planning.

A plan is a representation of a course of action, usually given as an ordered set of goals (Cohen & Feigenbaum, 1982). For the plan to be executed in the real world, the goals must be interpretable as operations that can be carried out in that world. For example, a military plan might consist of the ordered goals: "capture this bridge, while defending this piece of ground; then cross the river and seize this enemy position". This plan can be carried out if the executing units understand the meaning of the operators "capture", "defend", "cross" and "seize". The plan itself can be considered to be a hierarchical structure that consists of nested subgoals. "Crossing the river" in the example might require first that the bridge be checked for damage and repaired if necessary, then that the individual military units cross in a certain order.

The process of planning is basically a search for the ordering of the operators that will achieve the primary goal. Processes for planning have been most extensively studied in the field of artificial intelligence, where a particular approach to planning, called the hierarchical approach, was developed. In hierarchical planning, a rough (vague) plan is developed first and then the rough parts are refined into detailed subplans and hence into a sequence of defined operators. The key characteristic of this approach is that it uses a hierarchy of plan representations during the planning process itself. This has the advantage that the details of planning do not become computationally overwhelming. This model has been extensively refined, but is not based on evidence from studies of human planning.

Hayes-Roth and Hayes-Roth (1979) have argued that a strict top-to-bottom, coarse-to-fine approach to plan development is not characteristic of human planning. They based their conclusions on the analysis of humans solving a practical errand problem. The cognitive model of planning resulting from this work, called the "opportunistic model", proposes that humans plan via a multidirectional movement through a set of decision categories and observations that influence the plan development. Although the idea of different levels of plan abstraction is maintained in the model, the movement through these levels is not strictly top-down from development of an abstract to development of a detailed plan, as it is in hierarchical planning. It can have a strong bottom-up component: decisions about plan steps are influenced by immediately-obtainable goals (e.g.,

"convenience") that seem to be brought into focus by plan simulation. In general, planning is "opportunistic": planning processes are instigated by something that the planner notices about the state of the world as it is transformed through simulation of the plan so far.

The planning problem used in the Hayes-Roths' work was a loosely-constrained one in which subjects, using a map of a town and its shops, formulated a realistic plan indicating which errands from a list they would do, when they would do them, and how they would travel through the geographic area among them. Subjects used their own experience in shopping to guide their plan development, for example, they allocated a certain amount of time for accomplishing a certain kind of errand. The degree of detailing in the final plan was not controlled, as the plans were not executed as such. We have developed a similar, but more tightly defined planning task, set in an environment called SPLITS, that we argue is more typical of command and control (McCanli & Essens, 1991). In our task, subjects are required to plan the most efficient way for shopping robots to pick up commodities in a grocery store, while at the same time satisfying certain constraints. Subjects are permitted use of limited paper and pencil planning aids. They are encouraged to try and optimize their solutions and their plans must be developed in enough detail to be actually executable by the robots, whose capabilities are limited to moving through the aisles and picking up items. In the SPLITS paradigm, the plans developed by subjects are executed to provide feedback on the solution, and there is a well-delineated distinction between planning and execution.

Ultimately in our research, we are interested in determining whether the opportunistic model holds for SPLITS-type tasks of planning in time and space. In particular, we wish to determine whether and how the nature of planning changes over repeated exposure to the same kind of problem.

However, the first step in this line of research is to determine the basic cognitive processes and procedures used in planning in SPLITS tasks. This step is necessary because there is relatively little known about how people approach planning in tasks of this complexity. It is this analysis that is reported here.

Thus, there were two main goals in this study. The first goal was to develop a method for analyzing the cognitive processes associated with planning for SPLITS problems in time and space. This was done by capturing the planning process and developing a coding scheme for interpreting the protocols given in the process. We were especially interested in seeing whether different levels of plan abstraction were used during planning. A subsidiary goal to this main one was to confirm that the SPLITS planning task could be accomplished by subjects and that the paradigm could be executed as expected.

Our second goal was to develop a model for efficient planning in this task, based on observations of planners and assuming a hierarchical approach to planning.

This model will be tested in a future experiment to determine the degree to which planning in this task conforms to the hierarchical versus the opportunistic approach.

2 METHOD

2.1 The planning task

2.1.1 *General*

Planning was carried out in this study using a simple implementation of a manual version of the SPLITS environment. SPLITS is a general environment for studying human and computer-aided planning in time and space. The overall conceptual design of SPLITS is described in a separate report (McCann & Essens, 1991). A brief description of the basic manual version of SPLITS is given here.

In the basic version of SPLITS, subjects are required to plan how to pick up commodities in a grocery store using shopping robots. The store is presented as a two-dimensional matrix with aisles and shelves containing grocery commodities (e.g., eggs, green beans, bread) grouped in categories (e.g., dairy, vegetables, baked goods). The shopping robots have different characteristics: for example, robots could have different speeds of travel through the store, and hold different numbers of commodities in their baskets. The overall task of the subject in a session is to plan for the efficient pickup of the items on a shopping list, using the robots available. The task may also have certain constraints on the order of pickup of commodities.

In this version of SPLITS, planners make their plan using completely manual methods. They are given a "planning board", a paper map of the store with commodity locations marked, and a number of colored pencils. Planners are free to mark the planning board in whatever way they wish as they are creating their plan.

Once the plan has been detailed to the planner's satisfaction, it is played out step-by-step by the experimenter on a separate execution board. In this "execution phase", the subject gives orders to the experimenter on how to move the robots through the store and when to pickup items. The robots are represented by markers that are physically moved on the execution board. When orders are given for the pickup of commodities, these are physically placed in the robots' baskets. At the end of each cycle of movement and pickup, the store clock (represented by a counter) is advanced one tick.

Although subjects are encouraged to make as complete a plan as they can before execution starts, they are permitted to stop at any time during execution to do more planning or to do replanning. During this time the store clock does not run. The execution done to that point cannot be revoked; subjects must plan on the basis of the current location and state of the robots.

2.1.2 *The store layout and shopping list*

Two basic store layouts were used in this study, each organized on a matrix 15 x 10 (Fig. 1). Each type of layout had 10 blocks available for arranging commodities, each with slots for 6 commodities. In one type of layout, the blocks were arranged as linear rows of commodities; in the other they were organized more as islands. The blocks corresponded to 10 categories of grocery store commodities: baked goods, fruits, vegetables, meats, condiments, drinks, snacks, dairy products, cooking products, cleaners. Six specific commodities appeared in each category. Under the category condiments, for instance, the commodities were hagel, jam, peanut butter, sambal, vinegar and mustard. For each of the two types of layouts, five random assignments of commodity categories to available blocks was made, and then the six commodities within the category were further randomly laid out within the blocks. The commodities in each category were the same in each case. One square on the matrix was designated the entrance (labelled "IN") and a square on the opposite side of the board the exit (labelled "OUT"). Thus there were a total of ten different layouts of store commodities.

Shopping lists were created by randomly choosing 15 items from the total commodity set of 60, ensuring that at least 9 out of the 10 groups were represented in the list by at least one commodity. Twenty lists were so created and assigned randomly to the ten layouts, thus giving a total of 20 problem spaces (combination of list and layout). Three were selected as problems for the training sessions. From the remainder, a different random selection of 12 for each subject was made for the test sessions.

Paper "planning boards" for each problem were created consisting of the store layout and the shopping list (Fig. 2). A large version of the layout was created for use as the execution board.

2.1.3 *Specific task used in the study*

The task in this study was to create a plan for efficient pickup of all items on the shopping list. The subject had available two robots: a red robot that travelled one square per tick of the store clock; and a blue robot that travelled two squares. The robots travelled along the aisles in the store. They could travel simultaneously, that is, both could travel during one tick of the store clock. However robots could also rest on a square for one or more ticks.

 commodity slot

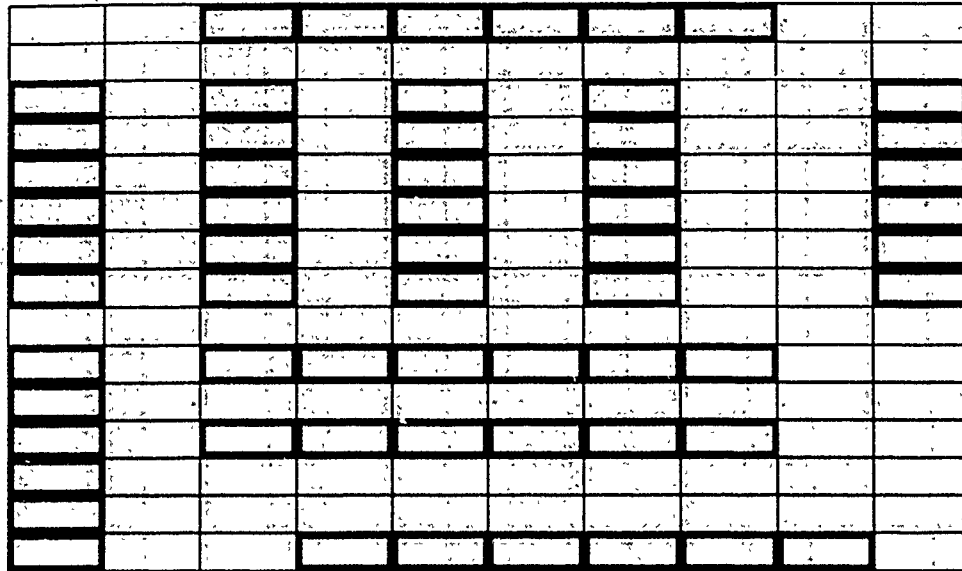


Fig. 1 Two basic store layouts used for planning task.

oranges
Brillo pads
cake
mustard
sambal
flour
beer
chicken legs
Spa
hagel
gum
apples
lettuce
dish soap
butter

Fig. 2 An example of a planning board.

The shopping basket of the red robot could hold 10 items; and that of the blue robot held six. A robot could pick up an item if it passed the item. Robots could also transfer items between their baskets if they were standing on the same square. A transfer cost one tick.

In addition, there were three constraints with which the plan had to comply:

- a) Items in the *drink* category had to be placed in the bottom of the basket;
- b) Items in the *baked goods* category had to be placed at the top of the basket;
- c) The *dairy products* had to be picked up near the end of the time in the store.

The first two of the constraints were absolute: the robot/experimenter would refuse to pick up an item during plan execution if it violated the constraint. The third constraint was left open to interpretation by the planner. These constraints also applied when a transfer was made.

Both robots were standing on the "IN" square at the start of planning. The planner was instructed to make and execute a plan that picked up all the items on the list, complied with the constraints, and minimized the time that the robots spent in the store. The task was complete when all items on the list had been picked up and both robots stood on the "OUT" square of the execution board.

Three simpler versions of the planning problem were used to familiarize the subjects with the task and to give some practice in providing think-aloud protocols. The first required pickup of 15 items using only one robot (speed 2 squares per tick) whose basket capacity was 15. There were no constraints in this problem. The second training task used a robot with speed one square per tick and also required that all the constraints be satisfied. The third training problem introduced two robots (red and blue) for accomplishing the task, but without the constraints on pickup.

2.2 Procedure

Participants were seated at a table in front of the planning board, which was fastened to the table. Colored pencils and an eraser were available on the right. The experimenter sat on the planner's left. The execution board was mounted on a small stand in front of the experimenter, easily visible to the subject, but far enough away that the planner could not conveniently point to it. A video camera was focussed on the planning board and recorded all interactions with the board. The video recording included a time code. An additional recording was made of the audio only.

The planner read first a general written introduction to the task, including a description of a typical store, the general idea of the planning task and how the execution of the plan worked. Three training sessions were then given. Three sessions with the full test problem with different layouts and lists were carried out on four subsequent days. For each session, explicit written instructions were provided concerning the rules and conditions for the problem. In each case, the task of the subject was stated as follows: "Plan and execute the pickup of items on the shopping list so that it is done in a minimum number of clock ticks. The robot(s) must be at the square marked OUT for the plan to be complete." Subjects could refer to the written instructions during planning if required.

During the planning phase, participants were required to give a running verbal account of the plan development. The planner was under no time pressure during this phase. Once the plan had been completed to the subject's satisfaction, it was executed on the execution board. Execution took the form of orders given to the experimenter who played the part of the robots. The orders were of the form: "Red moves one square down and picks up carrots; blue moves two squares right, no pickups". The experimenter played out the orders on the execution board precisely as given, except in the case where a pickup would violate the rules given in the task (e.g., the carrots would be placed on top of the cookies in the basket). At the end of each cycle of move/pickup, the counter representing the store clock was incremented. The total number of ticks required to satisfactorily complete the task was recorded.

The protocols of two planners solving 12 different versions of the planning problem were collected in this study. Both had been educated to a graduate university level.

2.3 Analysis method

Six of the twelve problem sessions carried out by each planner were selected for detailed analysis. (Not all protocols were analyzed due to the amount of labor involved.) They were evenly distributed in time over the 12 sessions. The data were treated as pooled over the sessions.

The verbal transcripts from these sessions were first transcribed into written form. The videotapes for the planning sessions were reviewed together with the annotated planning boards created during the trials. For each problem, a graphical map was made identifying and labelling the annotations made by the planner (e.g., lines designating routes); the location of deictic references (e.g., a transfer point indicated by the word "this"); and other spatial areas of focus referred to during planning. Following this, a scheme for coding the graphical interactions of the subjects with the objects on the planning board was developed. The graphical protocol for each problem session was then coded from the

videotape with the help of the graphical map and inserted alongside the written verbal protocol to produce a verbal plus graphical protocol.

The verbal+graphical protocol provided the material for the main analysis, which was conducted according to the procedures for analysis of verbal protocols outlined in Ericsson and Simon (1984). In the first stage, we identified the objects manipulated or used by the planners in creating a plan. Analysis of the verbal+graphical protocols lead to the identification of a set of primitive planning actions involving these objects or concepts. Common actions were then grouped into categories.

The following section gives the results of the above analysis and, in addition, identifies three levels of abstraction at which planning was conducted. The subsection giving the description of the levels of plan specificity is followed by a complete verbal+graphical protocol for one problem in which a plan action code is applied and the level of abstraction of plan development is identified chunk-by-chunk in the protocol. The section concludes with some general observations on the planning behavior of the two planners.

3 ANALYSIS

3.1 Objects and concepts used in planning

Planners used a vocabulary of objects and concepts in the process of carrying out the planning task. Some of these were given explicitly as part of the problem domain, for example, the store and its commodities, the robots, the rules for arranging items in the basket or for transferring items between robots. Certain concepts (e.g., the store) had a physical representation which was manipulated during planning; other concepts existed only at a more abstract level (e.g., the rules) and had no physical manifestation. Further additional objects and concepts were generated by the planner in the process of creating the plan, for example, routes, transfer events, transfer locations, pickup points. The first step in the analysis process consisted of identifying these objects and concepts. A list of them in tabular form is given in Table I. Note that the list has been compiled from objects and concepts used by both planners over all problem sessions. It was not the case that a given planner referenced all the concepts in creating a given plan.

3.1.1 Domain objects

The domain objects manipulated or created during planning consisted of the *commodities* in the store, the *store* itself, the *robots*, *routes* for the robots to follow, *pickup points* for commodities, and *transfers*. The first three types of domain objects were presented as part of the original problem statement; the

last three were concepts that were usually (although not always) generated by planners during the process of plan creation. In some cases the latter concepts were given some physical manifestation by the planner, e.g., a symbol, annotation, etc.

Robots can be described in relatively simple terms: there are two kinds of robots, labelled "red" and "blue" with *characteristics* basket capacity (11 items for red; 6 items for blue) and speed (1 square per tick for red; 2 for blue). Robots also have the characteristic that they "can transfer items". There is a physical representation of the robots in the execution environment, but not in the planning environment.

The concepts "store" and "commodities" are physically represented by graphics and labels in both the planning and execution spaces. Both have the property that they can be described using a *hierarchy* of specification. The store can be considered as a spatial partitioning into aisles and shelf blocks. At a lower level of detail in the *spatial hierarchy*, the aisles can be considered in terms of individual component squares (including the special squares "IN" and "OUT"); and the shelf blocks can be considered as slots in which the commodities are placed. The commodities have a natural *categorization hierarchy* presented explicitly as part of the original problem: there are groups of items (e.g., drinks, dairy, meat) and individual items contained within the group (orange juice, cassis, beer, etc.). In addition, the planner sometimes *partitions* the items into convenient categories during plan creation. This partitioning can be on a spatial basis ("this group of items here / the rest"). Or it can be on the basis of commodities that are affected by the rules (e.g., Spa, cookies, bread, butter and yogurt) versus the remaining items on the shopping list. Another kind of partitioning is a division of the shopping list into those items to be picked up by red and those assigned to blue.

Some of the concepts or objects generated by the planners also have a hierarchy associated with them, but of a slightly different kind. We term this a *specification hierarchy*. Routes for robots to follow may be specified approximately by the planner by being traced (but not drawn) on the planning board; routes may, by contrast, also be drawn heavily, square-by-square, with the pickup points also marked. Similarly, the concept of transfer of goods between robots has different levels of specificity. The very existence of a transfer event is a first level of detailing. Once the need for a transfer is established, it can be considered from two perspectives: in terms of spatial location (where in the store does it occur?) and in terms of the items that are transferred. The location can be specified grossly as a general area ("around the milk") or it can be pinned to a particular square in the store. The transferred items can be described simply as the number of items ("blue will give red two items") or in terms of the precise items to be transferred ("blue will give red the butter, and cookies").

Table I Domain objects and concepts

Objects & Concepts	Type	Subdivisions Used
Domain Objects	Commodities	category hierarchy * - groups of items (e.g., drinks, vegies) - individual items (e.g., carrots, milk)
		partitioning ** - clusters of items (spatially grouped or grouped by assignment)/ individual items - "special" goods (i.e., linked to rules)/others *
	Store *	spatial hierarchy - aisles and shelf blocks - specific squares (e.g., holding item; IN; OUT)
	Robots *	partitioning - red with characteristics: basket capacity of 11; speed of 1 sq/tick; can transfer - blue with characteristics: basket capacity of 6; speed of 2 sq/tick; can transfer
	Routes **	location hierarchy - traced - drawn - drawn with pickups
		partitioning - whole route (for robot)/route fragments
	Transfer **	existence location hierarchy - trans area - trans point (i.e., sq) transferred item hierarchy - trans "basket" - trans number - trans specific items
Rules/Conditions *	Pickup points **	location hierarchy - pickup area - pickup point (i.e., square)
	for placement	B1 - drinks on bottom B2 - baked goods on top B3 - dairy near end
Goals	for transfer	T1 - robots must be on same sq to transfer T2 - transferring costs a tick
		goal hierarchy - main goal*: transport all goods listed in shortest time to OUT - subgoals **

* denotes given objects or concept; ** denotes subject-created object or concept

3.1.2 Rules and goals

The concepts discussed above are represented as physical objects in the problem domain. There are other concepts -- the rules for behavior of robots, the goal of the planning task -- that are also manipulated during planning. The following rules and goals entered into subjects' plans:

- a) Basket rule 1 - Drinks must be placed on the bottom of the robot's basket
- b) Basket rule 2 - Baked goods must be placed on the top of the robot's basket
- c) Basket rule 3 - Dairy products must be picked up near the end of the time in the store
- d) Transfer rule 1 - Robots must be on the same square to transfer items
- e) Transfer rule 2 - Transferring costs one tick
- f) Main goal - Using the resources, transport all items listed to OUT in the fewest number of ticks.

The objects and concepts identified above are the targets for the planning actions described in the next subsection.

3.2 Planning actions

The analysis of the verbal and graphical protocols of the two planners permitted identification of a set of primitive planning actions that accounted for the majority of the subjects' activity. About 90% of the verbal and graphical actions was accounted for by the coding scheme. The remainder were comments or questions to the experimenter, or protocol fragments for which there was no adequate code. The coding was done by one person, so the reliability of the coding scheme was not assessed.

The actions can be considered as operators that either create or act upon a target object or concept. The set of primitive actions, their associated objects and modifiers, their definitions, and examples are given in Table II. Columns 2-5 give the syntax of the action. The action name is given under the heading "Plan Action", and the target of the action under the next column, "Target". Additional special Modifiers of the action are shown in the next column and the Robot, if applicable, in the subsequent one. For example, the action *order pickup* sets the possible order for pickup of certain target objects. The target of the action could be individually-named *items*, a *group* of items, or a *cluster* of items. In addition, the action might be modified by an assignment of the pickup to either the *red* or *blue robot*.

Table II Codes and definitions for plan actions

Note: The examples given here are not necessarily verbatim from the protocols studied.

PLAN ACTION CATEGORIES	PLAN ACTIONS	TARGETS	MODIFIER	ROBOT	DEFINITION	EXAMPLE	
						VERBAL	GRAPHICAL
ORIENT	Note problem requirements				Review or re-read requirements of the exp't task	"plan and execute so that it is done in a minimum of store clock ticks" "I have to pick up everything on this list"	
	Note resources				Review the robots' characteristics	"I have two robots, a red and a blue" "blue takes 6 items but it moves 2 squares"	
	Note rules				Review or re-read the rules for order of item pickup	"alright, always something that needs to go on top" "dairy near the end" "cookies have to be at the end"	
	Note locations	groups item(s) IN, OUT			Make note of location of items relative to one another and to entrance/exit	"the baked goods are actually near the exit"	
	Translate rules in context				Interpret the rules in the context of the particular layout	"well, we've got lots of dairy" "the beer is quite near the IN square, so that shouldn't be a problem" "I think the cookies on top will not be problem at the transfer"	
	Form group				Define a partitioning of the items or layout	"I have four products here that have to be taken near the end of the shopping"	scope item (set)
	Transform representation				Mark the spatial locations of items on the layout	"I'm gonna circle the items" "we'll make that 'top', cake"	marks items annotates "top" on item cake

continued...

Table II continued

PLAN ACTION CATEGORIES	PLAN ACTIONS	TARGETS	MODIFIER	ROBOT	DEFINITION	EXAMPLE	
						VERBAL	GRAPHICAL
ADOPT STRATEGY		from rules, layout			State a characteristic that the plan should have, possibly as deduced from the rules/layout	"I'm trying to find a place where we can make red do slightly less work at the expense of blue" "I have to get the red the quickest way to the OUT" "I should not move the red one too far up; it takes too many moves in relation to the blue" "I have to move the robots as much as possible simultaneously" "the red one has to be empty when the items are handed over, so that drinks can go on the bottom"	
	Assign item [with order]	item cluster(s) (spatial) item group(s) item(s)		to red to blue	Allocate the pickup of the items to particular robot; a specific order of pickup can also be implied	"red'll pick up the dairy products at the end" "red's gonna come in and pick up the Spa" "blue's going to get ham, eggs, window cleaner..." "the pina colada has to be picked up first"	
CREATE/MODIFY PLAN	Order pickup	of item cluster(s) of item group(s) of item(s)		{for red} {for blue}	Set a possible order for the pickup of items, either within an item set or within the execution period	"red's going to cruise down" "red's gonna come right down and out, the most efficient route" "somebody's going to go in this direction" "blue will go like this..."	draws route (1) draws route (B1)
	Construct route	route, routefrag		{for red} {for blue}	Define a route or partial route [for a robot]; it may be roughly traced out in the "air" or carefully drawn with pickups marked		
	Order route	route frags		{for red} {for blue}	Set a possible order for the execution of route frags [for robot]		
	Assign route	route, routefrag		to red to blue	Allocate a route or routefrag to be executed by robot	"this route to collect the sugar and oil will be blue's job"	
	Specify transfer event				Propose a possible transfer	"blue is going to run into red somewhere"	

Table II continued

PLAN ACTION CATEGORIES	PLAN ACTIONS	TARGETS	MODIFIER	ROBOT	DEFINITION	EXAMPLE	
						VERBAL	GRAPHICAL
CREATE/MODIFY PLAN	Specify transfer location	transarea transpoint			Specify the location of the transfer event	"blue should come and help red around here" "blue will meet red by the milk" "it would be better to make a transfer here"	scopes area (upper right)
	Specify transfer commodities	"basket" number item(s)			Propose a possible transfer of goods in varying detail: the basket contents, the number of items or the specific names	"here a transfer will happen" "blue gives off these items" "blue dumps it on red" "he gives the melons to the red one"	point square (TP1) mark square (TP3) points to baked goods
	Modify assignment	item cluster(s) (spatial) item group(s) item(s)	from red from blue	to red to blue	Change the working item assignment by re-assigning items from one robot to the other	"no, blue will not pick up roasted nuts" "red'll have to pick up the onions instead of blue"	
	Modify route	route, routefrag	by routefrag	[for red] [for blue]	Change a proposed route by adding or removing a routefrag	"that'll be an extra move" "oh no he has to go through here first to pick up the butter"	modify route B1 by B8 scope aisle (MH); point item (butter)
	Modify transfer location				Change the working location of the transfer	"so the handover will be here by the worst instead"	point square (TP2)
	Modify transfer commodities				Change the number/names of goods transferred	"blue should only give red four items instead of five"	
	Balance	through assignment, route (tics)	between red & blue within red, blue		Adjust the assignment of items to/between robots to equalize the route ties	"blue'll get the milk since he'd be waiting for red anyway"	
	Specify pickup point	for item		[for red] [for blue]	Mark or indicate the location at which an item will be picked up	"red gets the butter now ..."	marks pickup (butter)
		of rule, order, assignment, route	on route on assign on order	for red for blue	Determine the implications of the current route, assignment, order on other, yet undeveloped parts of the plan	"if red picks up the cookies he can't pick up the worst"	
	Measure route time	of route, routefrag			Estimate or count the number of ticks for a particular robot to travel a route	"red's gonna move 1-31 (counts)" "it's 15 steps from here"	follow route (B2; part B3)
DEDUCE IMPLICATION							
MEASURE PLAN							

Table II continued

PLAN ACTION CATEGORIES	PLAN ACTIONS	TARGETS	MODIFIER	ROBOT	DEFINITION	EXAMPLE	
						VERBAL	GRAPHICAL
MEASURE PLAN	Compute route time	for route, route/frag			Compute the time taken for a robot to travel a route based on previous measurement	"10 steps to here and then another 3 is 13 in total"	
	Measure no. items assigned	on route			Count the number of items assigned to a robot	"blue will have 1-6 (count) things"	
	Check against rule				Assess plan against rule (for drinks, baked goods, dairy)	"so I have met all the criteria"	
	Check all items		against rules		Check that all items are picked up	"now, did I get everything? ... yes"	
EVALUATE PLAN	Check against capacity			[for red] [for blue]	Ensure that the basket capacity of the robot is not exceeded on a route	"did blue have enough room for all of these? no"	
	Assess total time				Check that total tick length is satisfactory	"far too many places!" "that's a waste of time, I think"	
	Compare time	for routes			Compare the route ticks for red and blue	"under 30, that's what I like to see"	
	Accept	plan (route, assignment, order)			Add the proposed route, assignment or ordering to the working plan	"there's 8 more steps that red has to take (than blue)" "it costs me less moves"	
CONCLUDE	Reject	plan (route, assignment, order)			Reject the proposed route, assignment or ordering for the working plan	"yeah, I'll do it like this"	
	Join routes				Join two routes together (usually with a small line)	"I don't like that plan at all"	
CONSOLIDATE /REVIEW	Redraw	route, route/frag			Redraw route(s) that had been previously drawn. often in order of intended execution	"that won't work"	join route (B4, B2)
	Remark	item, transfer point, pickup point			Remark points that had been previously marked	"so the cookies should be picked up here"	redraw route (B1)
	Review				Rename previously assigned items, routes, usually in order of intended execution	"Let's see if I remember what I wanted to do: blue goes up here ..."	remark pickup point (cookies)
						"Now I have all the items in this part"	scope area (upper left)

Certain of the primitive planning actions had common characteristics and were therefore aggregated on the basis of similarity into eight categories (column 1): orient, adopt strategy, create/modify plan, deduce implication, measure plan, evaluate plan, conclude, consolidate/review.

It is convenient to discuss the planning actions in a different order than they are given in the table. The bulk of the planning actions fall into the category create/modify plan. They will be described first. Actions that lead to deductions about one part of the plan on another part will be discussed next, followed by measurement, evaluation, and conclusion actions. The orientation and consolidation actions will be discussed last.

The planning actions in the main category, *create/modify plan* are of four kinds:

- a) assignment of certain item(s) to be picked up by a particular robot;
- b) the ordering of the pickup of items in time;
- c) the construction of routes for robots to follow;
- d) the specification of transfer events.

The simplest kind of planning action is *assign item(s) to red/blue*. Here the planner allocates an item or set of items on the shopping list to one of the two robots for pickup, as indicated, for example, by the phrase "blue's going to get ham, eggs, window cleaner ...". The target of the action may be detailed, as in this example, or specified more generally as a group of items, not individually named, e.g., "red'll pick up the dairy products ...". Sometimes the planner has previously formed a spatial clustering or other partitioning of items that is used as the target of the action, for example, "these will be picked up by blue" where the word "these" is clarified by a gestural scoping of certain items on the planning board. Thus there is a range of levels of object specificity, from rough to detailed, that can be invoked by the planner in describing the target of the assignment action. Items for pickup may be designated roughly as a spatial cluster; by group name (possibly with accompanying scoping gesture); or by individual name (e.g., carrots, eggs) and specific pointing gesture.

A second kind of planning action, *order pickup*, involves the ordering of item pickup during the time span of the plan execution, e.g., "the pina colada has to be picked up first". As in the case of *assign item*, the target of the action may be specified roughly (e.g., "first I'll get the things at the top of the store, then those at the bottom") or in detail, by name. There were also instances in the protocols in which the ordering of pickup was folded into a statement assigning an item or group of items to a robot, for example, "red'll pick up the dairy products at the end".

A third kind of planning action involves the construction of routes for the robots to follow in picking up items: *construct route*. Sometimes the route is loosely described in verbal form, for example, "red's gonna come right down and out, the

most efficient route". In many cases, the planner graphically traces the route out on the planning board, sometimes without actually marking the board, other times, drawing the route out explicitly. Often, only a portion of the total route for a robot, named a "route frag", is drawn at a time. Once several route frags have been created, then the order of their execution may be explicitly designated by the *order route* action. In almost all cases, the route or route frags so constructed are immediately assigned to either the red or blue robot. If this was not the case, they could be later assigned to a robot by the action *assign route*. The construction of a route usually implies that the items on the list that lie along the constructed route are to be picked up by the robot that follows the route. The planner sometimes marks the pickup points of items explicitly (by *specify pickup point*), especially if the route passes items that are on the list but that are not intended for pickup at that time.

In addition to the construction of routes, the planner may also specify the transfer of goods between robots, usually from the blue to the red since the red basket capacity is greater. Sometimes the planner first establishes the need for a transfer to take place (*specify transfer event*) and then later determines the location of the transfer (*specify transfer location*) and which items are to be transferred (*specify transfer commodities*), as in the following sequence of phrases:

"blue is going to run into red somewhere"..
 "blue will meet red right by the milk"..
 "blue gives off these items" points to baked goods

Both the location and the item set can be specified in varying levels of detail. In the example, the location of the transfer is relatively precisely defined, whereas the items to be transferred are not detailed individually, but are simply categorized under the heading "baked goods".

It was typical that the plan, as defined by routes, assigned pickups, and transfer events, underwent revision as the planner worked. The following plan actions covered the cases where the current working plan was changed:

- a) *modify assignment* - change a previous assignment of items to a robot by de-assigning (e.g., "no, blue will not pick up the roasted nuts") or re-assigning (e.g., "red'll have to pick up the onions instead of blue")
- b) *modify route* - change a proposed route for a robot by adding or removing a route frag
- c) *modify transfer location* - change the working location of a transfer event
- d) *modify transfer commodities* - change the items to be transferred.

During the construction of the plan, the planner's protocol sometimes provides a chain of deductions that lead to a conclusion about how a particular move will influence or constrain later moves by the robot. For example, the planner may

reason that "if red picks up the cookies, he can't pick up the worst" (presumably because of the rule that no item can be placed on top of baked goods in the basket). These kind of actions have been designated *deduce implications*. In the example, the deduction stemmed from the assignment of cookies to the red robot. Deductions can also be made based on the order of pickup, the route proposed for a robot, etc. Furthermore, since the moves generated for one robot can also have implications for the other robot, the deduced impact may be upon the other robot.

Sometimes the planner alluded to goals or intentions about plan actions to be taken. These intentions were derived from characteristics that the plan per se should have. These actions were coded as *adopt strategy*. The subject might say, for example, "I have to find a route where the drinks can be picked up so that they go on the bottom". In this case, the desirable plan characteristic is that the drinks must go on the bottom of a basket. In other cases, the planner might not be so explicit about his intention, e.g. "the robots should move as much as possible at the same time". Here the assumption is that the planner then adopts the strategy of finding such a plan, but the procedure for achieving the goal may not be explicitly stated.

Part of the planning task involved the measurement and evaluation of the plan. Plan measurement concerned mainly the counting or computing of the number of ticks that it would cost for a robot to travel a proposed route (*measure route time, compute route time*); and the counting of the number of items that would be picked up by a robot following a route or route fragment (*measure no. items assigned*). Several different kinds of evaluation actions could then be carried out. The planner might *compare the time* that it would cost for red and blue to travel their two routes simultaneously, as in: "that's 8 more steps that red has to take than blue". The underlying motivation for this action is that the routes should be of equal length for the plan to be efficient. Or the planner might *assess the total time* that a plan would cost, to see whether the time is "satisfactory", e.g., "under 30, that's what I like!". The planner must also ensure that the basket capacity of a robot will not be exceeded at any point (designated *check against capacity*). Other kinds of evaluations are made to ensure that the rules are being satisfied and that all items on the list are picked up.

Related to the evaluation of the plan or parts of it were conclusions by the planner to either *accept* or *reject* the proposed assignment of items to robots, the ordering of items for pickup or the proposed route/route/frag. Statements like "yeah, I'll do it like this", or "that won't work" indicate that the planner has made a conclusion about the plan or a part of it.

Two other categories of planning action were also observed. In one category, designated *Orient*, the planner focussed on the problem requirements, the resources for solving the problem, the rules and the layout of the store. These kinds of actions, which usually occurred at the beginning of the planning process

or at the beginning of a new phase of planning, served to refresh the information concerning the problem and its constraints. For example, the planner might *note rules*, that "the cookies have to be near the end". The implications of the rules might also be considered, as in "I think the cookies on top will not be a problem for the transfer". This kind of action was designated *translate rules in context*. Another kind of orienting action occurs when the planner *transforms the representation* of the problem by marking the items on the shopping list on the store layout.

The counterpart of the Orient category was the Consolidate/Review category, whose actions usually occurred at the end of a planning phase. Here the planner would *join routes* together in sequence, *redraw* the routes, *remark* the transfer or pickup points and, in general, *review* the plan.

3.3 Levels of plan specificity

The planning actions described above operate on the objects and concepts given in the task (e.g., commodities, store layout, robots) to transform them into a new set of objects and concepts that make up the plan (e.g., routes, transfer events, pickup events). The plan itself can be characterized in differing degrees of detail. A rough plan may call simply for "the red robot to go through the center of the store, while the blue robot picks up items on the periphery". This level of plan detailing is insufficient to ensure that the task can be satisfactorily accomplished during the execution phase. There is not enough detail established to determine whether the rules for pickup will be satisfied, or indeed, whether all the items on the list will be picked up. For the plan to be satisfactory, it is necessary that the planner decide fairly precisely how the robots are to move, and at which points in the sequence of move events the pickups and transfers are to occur. Finer detailing is required if the main goal of the plan is to be accomplished, that is, if the time that the robots spend in the store is to be minimized. In this case, the planner must attempt to eliminate all unnecessary moves by considering step-by-step the actions of the robots and how they are co-ordinated against each other.

The verbal and graphical protocols give evidence that planning is carried out at different levels of detail. We have been able to distinguish three levels of detail on which planning occurs. The first level (Level 1) involves a very rough assignment of commodities, ordering of commodity pickup or routing of robots. The verbal indications of planning at this level are, for example, gross assignment of items (e.g., "these to red and the rest to blue"); rough ordering of item pickup, often based on two or three major spatial clusters of items (e.g., "this group of items first and then those"); and rough descriptions of routes (e.g., "one robot will circle and the other will go over and down"). Gestural evidence of planning at Level 1 includes scoping actions covering large sections of the store on the planning board (possibly using the whole hand) to define clusters of items or to

propose routes. At this level, the possibility of a transfer is considered, but no details of its location or the items involved are provided. The plan at this level is rarely evaluated.

Planning at a second level of detail involves a firmer specification of item assignment, pickup ordering, route construction and transfer specification. Assignment of items to robots and the ordering of pickup is done on the basis of groups of items (e.g., vegetables), or on the basis of previously-defined clusters. Routes are structured by references to spatial divisions like aisles, and the planner may use back-and-forth motions along an aisle to show a general pathway. Proposed routes are constructed by being traced with a finger or sketched lightly in pencil, often with rounded corners. The drawings are accompanied by verbal descriptions that are non-specific, e.g., "red will go something like this". The transfer area is determined (within 2 or 3 squares), and an estimate made of the size of transfer needed (number of commodities). For example, the planner might trace a route out (for blue) and at the same time say "he could pick up the items here and go through here and give all the items he has picked up to red". The planner will usually ensure that the capacity of the robots' basket is adequate for the assignment, but this assessment is rough. The evaluation of the timing of the plan (on the basis of robot speed) is still coarse. There may be some tuning of the times for red and blue routes, but the measurement and comparison is approximate, as indicated by phrases such as "blue has to wait too long here for red" or "these routes cost about the same".

Planning at Level 3 involves the detailed assignment of items to robots, along with precise determination of the robots' routes (and thus the order of pick up) and the specification of the transfer. Planning at this level is characterized by consideration of individual items on the shopping list (rather than groups of items), and by the selection of the most efficient pickup points (squares). The following is an example of planning at Level 3 extracted from one planning protocol:

"red's gonna come in" draws route (R1)
 "and he's gonna pick up the Spa" draws route (R1)
 "and then he's gonna backtrack one and pick up the green beans"
 draws route (R1)
 "maybe even dodge for the onions" draws route (R1)
 "and might even go get the sugar" draws route (R1)
 "and then come back on his way so that he can pick up the cheese,
 cream and yogurt toward the end" draws route (R2)
 "and then head out the door" draws route (R2)

Route fragments or routes are drawn in detail, more heavily than at Level 2. The planner often counts the number of items to be picked up and computes the effects of the transfer of items to be certain that the basket capacity of the robots (especially the blue) is not exceeded. The measurement of route times

involves counting of the number of squares to be travelled, and attempts to balance the workload between the robots by re-assignment of single items and slight modifications in the route. The following protocol fragment is an example:

"if red goes gets the gum
red'll be sitting idle ...
red'll just be hanging out for the longest time
well, 7 moves or so
now if red were to ignore the gum
and get the salt
that would be 1-25 (counts) moves
and I think that's what I counted for blue"

Finally, in Level 3 planning, the exact square for the transfer is designated (and may be marked), and the items to be transferred are named and may also be annotated.

3.4 Detailed analysis of a protocol

Let us now see how the system for coding the planning protocols can be applied to the full protocol given by a planner for solving one planning problem. The analysis of one planning protocol is given in Table III. The second column in the table contains the verbal protocol of the planner, chunked into sections that are numbered for reference in the description below. The third column contains the graphical protocol (gestures and drawing) that was executed concurrently with the verbal. A legend giving the meaning of the graphical actions is provided at the end of the table. The map in Fig. 3 will also assist in interpreting the graphical activity. The map is a copy of the planning board showing the annotations made by the planner (items marked, routes drawn, etc.) and labelling the squares that are referenced in the graphical protocol. Thus, in phrase 26 of the protocol, the planner proposes that the blue robot should "go first through here to pick up the melons, the wax, the pineapples" and at the same time gestures ("scopes") the area around square "a" on the board, and then draws route "B2", a route intended for the blue robot.

The remaining columns in the table show the plan action codes applied to the planning activity. The core of the planner's activity is devoted to actually developing a satisfactory plan (in three levels of detail as discussed above). A Preplanning phase is devoted mainly to orientation on the problem requirements and the store layout and a Postplanning phase focusses on consolidating the final plan.

Table III Detailed analysis of a planning protocol

PROTOCOL		PLANNING ACTIONS				
VERBAL	GRAPHICAL	PREPLAN	LEVEL 1	LEVEL 2	LEVEL 3	POSTPLAN
1. Well I'll first indicate the items in the shop	mark items (on list)	transform representation				
2. pie, rolls, orange juice, roast beef, cassis, pork chops, yogurt, cookies	mark items (on list)					
3. melons, figel, wax, cooking oil, pineapples, butter	mark items (on list)					
4. 2,4,6,8,12,14 ... yeah	point items (on list)					
5. so the IN is here	point sq (in)		note IN			
6. the OUT is here	point sq (out)		note OUT			
7. I have two robots		note resources				
8. um well I ... I um have to move the two robots as much as possible at the same time		adopt strategy				
9. and I have to lead the red robot as soon as possible to the out, I think		adopt strategy				
10. while in that time the blue one can pick up items			specify transfer event			
11. and give it to the um...						
12. if I can do that in the time that the red robot moves to the out, I have the quickest way ... yes	scope area (across layout)	adopt strategy				
13. there are three restrictions			translate rules in context			
14. the cassis and the orange juice have to be at the bottom	scope group (drinks)					
15. moving the red one through here, he will come across the things later on	trace route/frag		construct route/frag for red?			
16. um, the yogurt and the butter have to be picked up later	point group (dairy)		translate rules in context			
17. and the pie, rolls and cookies ...	scope area (upper right)					

continued...

Table III continued

PROTOCOL		PLANNING ACTIONS			
VERBAL	GRAPHICAL	PREPLAN	LEVEL 1	LEVEL 2	LEVEL 3
18. um, so the um the blue robot h to go back	draw route (B1)				construct last route frag for blue
19. like this	draw route (B1)				
20. one possibility is that he meets the red robot somewhere around here	hold sq (TPI)			specify transfer location (area)	
21. where he can hand over the items	scope aisle (UH)				
22. in that case he can continue ...	hold sq (TPI)			construct route frag for blue	
23. no ...				reject route frag	
24. um, if the red one moves like this	draw route (R1)				construct first part route frag for red
25. well, he could pick up the wax and the melons,					assign items "melons, wax" (along route) to red
26. but then um maybe it's ... maybe the blue one should go first through here to pick up the melons, the wax, the pineapples	scope area (around a) draw route (B2)				modify assignment "melons, wax, pineapple" to blue construct route frag for blue
27. and give them here to the red one	draw route (R2)				construct route frag for red
28. his basket is empty then	draw route (B3)				specify transfer location (point) specify transfer commodities "melons, ..."
29. so he could go back and pick up the cassis, the orange juice	draw route (B3)				construct route frag for blue
30. um, now there we have a problem with these items, with this restriction ...	point group (drinks)				construct route frag for blue assign items "cassis, orange juice" (along route)
31. well that's not really a problem because the ...					check against rule for drinks

Table III continued

PROTOCOL		PLANNING ACTIONS				
VERBAL	GRAPHICAL	PREPLAN	LEVEL 1	LEVEL 2	LEVEL 3	POSTPLAN
32. I only have 6 items yet, so the um red one ... the blue one could give all the articles to the red one	point group (drinks)					
33. and then hand over the cassis and etc.			specify second transfer event			
34. the only problem is when he's here	hold sq (b)			compare route time	specify transfer location (point)	
35. the um red one has moved quite far				reject? transfer point		
36. and that's a waste of time					deduce implications - compute number of items remaining	
37. um, from here, I still have 1-9 items	mark sq (b) point items (set)					
38. which can be carried by ...						
39. PL: what are you thinking?						
40. nothing. ...						
41. well, 1-11 (counts)	followc route (R1, R2) tracec route				measure route time (up to second transfer)	
42. there are 11 moves here	note route length (sq b)					
43. so from that ... if I want to transfer items here	hold sq (TP3)					
44. and there are 1-9 here, which is a transfer point, you could say ...	followc route (R1, R2) note route length (TP2)				measure route time (up to first transfer)	
45. well; these items have to be near the end	define area (A)		form group	order pickup of group "near end" in time		
46. so somewhere when the red one is here	scope area (lower right)					
47. so ah I could ... I think this is possible, to have the ... pickup these items	scope items (melons, pineapple, wax)			assign group to blue?		
48. as 1-9	tracec route (B5) followc route (B2)			construct route/frag for blue measure route time		
49. so they will be here at the same time	point sq (TP2)				specify transfer location (point)	

Table III continued

PROTOCOL		PLANNING ACTIONS				
VERBAL	GRAPHICAL	PREPLAN	LEVEL 1	LEVEL 2	LEVEL 3	POSTPLAN
50. they can transfer items				specify transfer commodities ("items")		
51. then the blue one goes back 1-5	follow route (B3)				order routefrag for blue	
52. the um 5, for the blue one	hold sq (TP3)				assure route time for blue routefrag	
53. the, um ... the red one moves only 3 ... 4,5	hold sq (TP3) point pp (hagel)				compute route time for red routefrag	
54. so the red one could go and pick up the hagel					balance through assignment	
55. ah, well...	draw route (R3)				construct routefrag for red	
56. transfer items here.	point sq (TP3)				specify (second) transfer point	
57. then the blue one ... 2,3,5	hold sq (TP3) point items (cookies, rolls, pie, yogurt, butter)				deduce implication measure no. items remaining	
58. has to pick up the pork chops at least,	hold sq (TP3) point item (chops, beef)				assign item "pork chops" to blue	
59. and the cooking oil can be picked up by the red one	hold item (oil)				assign items to red	
60. or, well, perhaps the red one could go up and pick up these ones	hold item (chops)				modify assignment of "pork chops" to red	
61. because I lose moves when the red is sooner at the out square	scope area (A) hold sq (OUT)					
62. you will count the moves I lose here	scope area (A)					
63. and he has to go the butter and back	point item (butter)					
64. so I'll better have the red one go up	draw route with dots (R4)			construct last routefrag for red		
65. 1-17 (counts).	draw route with dots (R4)				measure last routefrag for red	
66. and the blue one goes up from here 1-8 (counts)	point sq (TP3) trace route			construct routefrag for blue	measure route time	

Table III continued

PROTOCOL		PLANNING ACTIONS			
VERBAL	GRAPHICAL	PREPLAN	LEVEL 1	LEVEL 2	POSTPLAN
67. oh, no he has to go first through here, to pick up the butter	scope aisle (MH) point item (butter)			reject route/frag	
68. 1-14 (counts)	trace route			construct route/frag for blue	measure route time
69. so I lose um ... I lose, well, ok, I'll do it like this				compare times	
70. here is a transfer	mark tp (TP3)			accept	remark transfer point
71. and here is a transfer	mark tp (TP2)				remark transfer point
72. then the red one goes up like this	redraw route (R4)			construct route/frag for red	
73. and the blue one goes through here	draw route (B4) redraw route (B1)			construct route/frag for blue	join routes (B4, B1) redraw route with arrow (B1)
74. yeah				accept	
75. 1-5 (counts).ok	point items (along route B1)			measure no. items assigned on route	
76. I can execute					accept
77.	redraws (B2, B3, B5)				redraw routes (B2, B3, B5)

Codes for the Graphical Protocol

The following codes are used to describe graphical actions:

- POINT - Planner indicates a location (e.g., of an item, transfer point) with a finger or pencil; there is no marking of the board.
 HOLD - Planner indicates a location and holds the finger or pencil on it.
 SCOPE - Planner delineates an area or (less frequently) a set of items or a set of groups; there is no marking of the board. General areas may be conveniently denoted by "upper right" quadrant etc. Areas can also be composed by a set of items.
 TRACE(C) - Planner indicates "in the air" a proposed route, but does not actually draw it. The suffix "C" is used to indicate that the Planner counts at the same time as the route is being traced.
 DRAW - Planner draws a route/route/frag as one action on the board.
 REDRAW - Planner draws over an existing route again (usually more heavily).
 MODIFY - Planner amends a previously-drawn route without erasing it. Usually this takes the form of an addition (e.g., insertion).
 FOLLOW(C) - Planner traces a previously-drawn route with pencil or finger, possibly counting at the same time.
 ERASE - Planner erases an existing route (or part of it) or a pickup or transfer point.
 (RE)MARK - Planner highlights (possibly using some code) the location of an item, square, group or aisle. Only objects previously existing on the layout are marked. Once marked, they can be remarked.
 NOTE - Planner annotates the board with a notation, usually numerical, e.g., a route length count, item count.

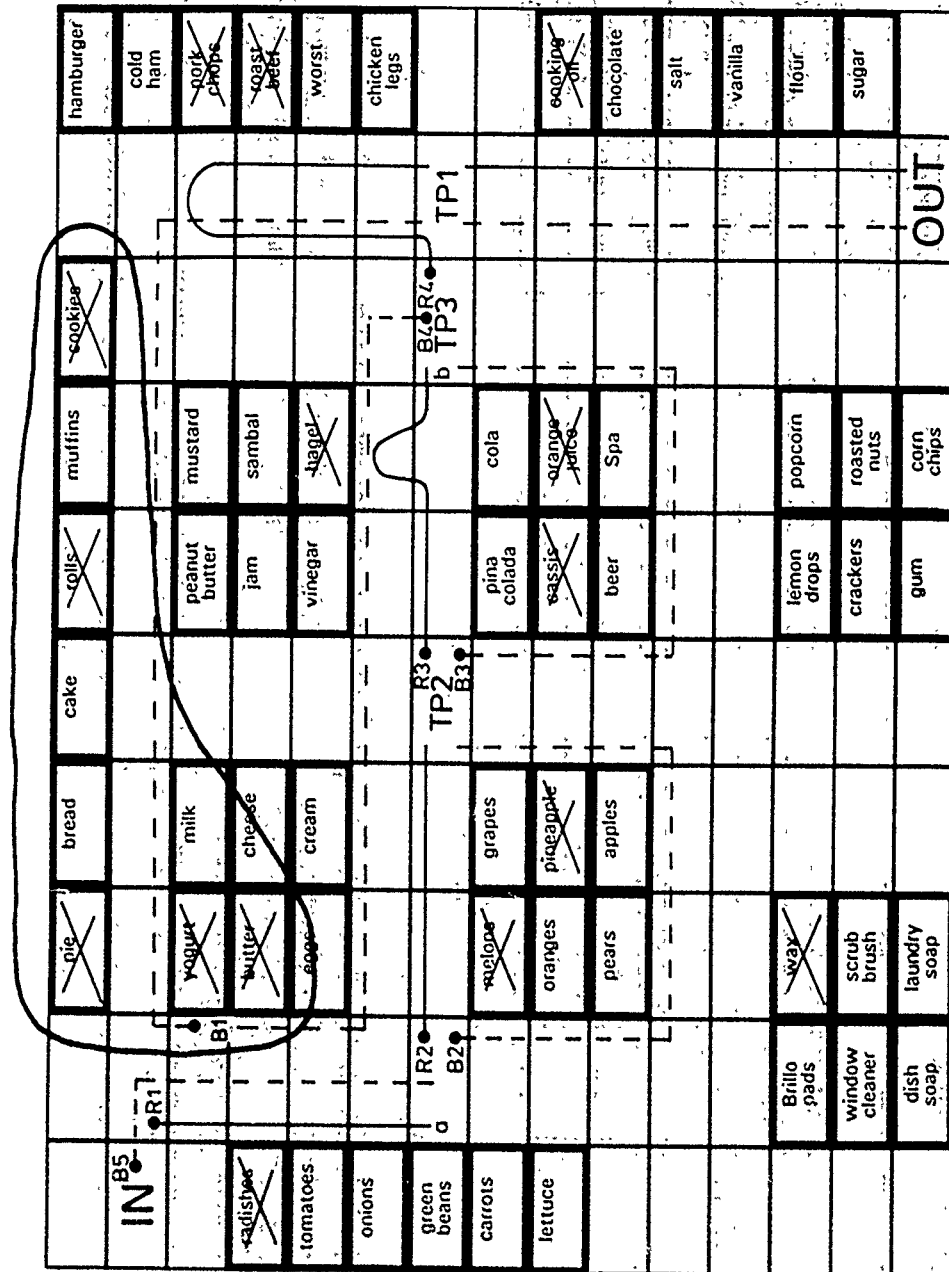


Fig. 3 Graphical map for sample protocol.

radishes
pie
rolls
orange juice
roast beef
cassis
pork chops
yogurt
cookies
melons
hagel
wax
cooking oil
pineapples
butter

In this planning protocol, the planner begins by marking the locations of the items given in the shopping list on the store layout. She then notes the resources available ("two robots", in phrase 7). She adopts the general strategy that the robots should move simultaneously as much of the time as possible and that the red should move as directly as possible from the IN to the OUT (phrases 8-9). In phrases 10 and 11, the possibility of a transfer event is mentioned. Since the event is simply proposed, and not given in any detail, the level of plan detail at this stage is rough and so the action is assigned to Level 1. The rules are then translated into a form that applies to this particular layout (i.e., "the yogurt and the butter have to be picked up later"). The rule concerning baked goods seems to prompt the detailed construction, in phrase 18, of the last part of the blue robot's route, labelled "B1" on the graphical map. Since the route is actually drawn out, the action is assigned to Level 3. The planner then turns in phrase 20 to consideration of the transfer itself, proposing that it should happen "around" the square labelled TP1. The use of the qualifier "around" indicates that this specification of transfer location is only approximate, and so the planning action is coded at Level 2. A possible route fragment for blue is considered briefly (only verbally) and rejected.

In phrase 24, the planner changes focus to the red robot and constructs a route (R1) down the aisle from the IN. She starts by assigning the pickup of wax and melons to red and then modifies the assignment so that blue picks them up instead. Assignments of items by name are coded at the most detailed level of planning (Level 3). The planner continues to work at this detailed level; first drawing route B2, then R2; then fixing a transfer point at location TP1 and finally constructing blue's route after the transfer (B3) to pick up the drinks (in phrase 29). A problem arises, because the planner still has in mind a second transfer after blue picks up the drinks, but blue cannot transfer drinks on top of the items in red's basket. As it happens, she has a solution for this situation (from previous sessions): she proposes a transfer of all goods from red into the blue basket, and then the reverse, where the drinks are selected to be transferred first¹. This move satisfies the rule concerning drinks always being on the bottom of the basket. There is yet a further problem, that the times taken by the two robots to move to the second transfer are unequal (noted in phrase 35), thus leading to inefficiency in the use of resources, since one robot (the red in this case) would have to wait for the other. No solution to this problem is proposed at this point (phrase 36) and the planner goes on to compute the number of items remaining to be picked up after the second transfer.

It appears in phrase 38 that planning has stalled, and the planner goes back to review the plan so far and to consider the time it would take for the robots to execute their paths (in phrases 41-56). To solve the problem of unequal route

¹ The other planner in this study did not discover this tactic.

times after the first transfer, a balancing of the plan is made in phrase 54: red is assigned pick up of the hagel. This balancing is done at a fine level of detail.

In the last part of the plan construction, the decision is made to have red go up for the pork chops and roast beef, while blue gets the dairy products and baked goods. Planning is done in two stages: first a tentative last route fragment (R4) for red is drawn using dots (in phrase 64), and the time for it measured. This planning is at Level 2, since the route is not firmly established. Then the time for the last part of blue's route (the portion between the square TP3 and the pickup point for the butter at the beginning of B1) is measured (in phrase 68). Although the two are not quite equal, red taking 17 ticks and blue only 14, the subject accepts those routes. The session closes with a firm construction of the route B4 and R4, and a redrawing of the rest of the route for blue, as consolidation. These actions occur as part of a Postplan phase.

The coding of the protocol shows that there is a gradual deepening, from Level 1 to Level 3, of information considered in the planning process and a concurrent detailing of the plan itself.

3.5 Preliminary observations on planning behavior

The two planners in this study took between 5 and 15 minutes to plan. Both began planning by marking the items from the shopping list on the store layout and briefly reviewing the rules. Subsequent planning was done primarily by sketching proposed routes out with red and blue pencils (corresponding to the routes for the red and blue robots). Planning did not necessarily follow a well-organized procedure, especially in the early problem sessions, when it was characterized by fragmented thought trains and frequent changes of focus. An example of this is to be found in the sample protocol (phrases 20-26):

"one possibility is that he meets the red robot somewhere around here
where he can hand over the items
in that case he can continue ...
no ...
um, if the red one moves like this
well, he could pick up the wax and the melons,
but then um maybe it's ...
maybe the blue one should go first through here to pick up the
melons, the wax, the pineapples"

Early planning seemed to be characterized by a search for an organizational structure upon which to base the planning procedure. Planning in later sessions was closer to the procedure that will be discussed in a following section.

The plans produced in this study evolved gradually, but it was possible to identify stages of plan development, corresponding to different levels of plan detail (as shown in the sample protocol). Planners usually developed only one plan and made no attempt to develop a second different one for comparison. The organization of the plan was anchored in time and space around the transfer event(s) and the entry and exit of the robots. (A transfer was not necessarily used in each plan produced; however, some plans involved two transfers and one three.) Plan development generally followed an expected chronological order of execution, so that events expected to be executed first were planned first. Both planners made an early split between the plan for the red robot and that for the blue, switching back and forth to focus on one and then the other so that the plans for the two were created in parallel.

An important strategy in solving this planning problem is to realize that red should go as directly as possible from the IN to the OUT square. Since red moves the slower of the two robots, this puts a lower bound on the number of ticks required to execute the plan and reduces the size of the solution space. Both planners used this strategy. One planner eventually adopted the approach of first counting the number of ticks on the direct pathway from IN to OUT to establish this lower bound. However, both seemed to have some initial difficulty in modelling the relative speeds of the robots: each expressed surprise at how "fast" the blue robot moved in comparison to the red.

Planners often simulated the execution of proposed plans or plan fragments. Simulation was carried out, for example, via the retracing step-by-step of proposed routes on the planning board with concurrent mention of which items were to be picked up. In cases where the planner was searching for a transfer point, the focus of the simulation of robot movement switched frequently back and forth between the robots.

Most of the plans produced were fairly "complete", in the sense that they could be executed without much further detailing or change. Occasionally the planner stopped execution briefly to consider how to proceed, but this did not result in a change in the original plan, only an amplification. In three of the sessions studied in detail, the planner discovered errors in the plan during the execution phase, and this resulted in replanning. In one case, the planner had neglected to pick up an item. In another case, the plan had not been completed during the planning phase; it seemed that the planner could not see how to efficiently resolve the pickup of one item near the end, and had decided to execute, possibly in the hope that the problem would be clarified.

How "good" were the plans that the two planners created? We gave a subset of the problems used in this study to two experts who had solved several similar versions in a previous pilot study. They were asked to spend as much time on the problems as necessary to produce the best solution (i.e., to minimize the number of ticks). On average, the solutions produced by these experts were around 26

ticks. The two planners in this study averaged about 30 ticks, although some solutions were considerably longer, especially if the planner had made an error. However, the plans produced by the two planners for a given list and layout were almost never the same in terms of the routes followed by the robots and the assignment of items to the robots for pickup.

Plan actions intended to be executed at the beginning tended to be developed in more detail than those for the end of the plan. Notable also was the fact that the two planners differed in the degree in which they detailed out the final plan on the planning board. One planner was satisfied with a simple drawing out of the robots' routes; the other marked, in addition, route directions (with arrows), pickup points for items and the transfer point(s). Both planners monitored execution by marking off the items on the planning board as they were picked up.

4 DISCUSSION

4.1 Planning behavior

The SPLITS paradigm as used in this study worked very well in evoking and capturing the planning behavior of the planners. The planning problem was hard enough that the solution was not obvious, but not so hard that planners could not find a plan (albeit in most cases, not the best) in a reasonable time. The procedure of using 12 sessions gave the planners opportunity to learn and to explore different strategies for solving the planning problem.

The planning behavior exhibited by planners in this study can be characterized as a search for a solution (a plan) that accomplishes the goal and satisfies the constraints of the problem statement. However, this search was not a process of simply selecting potential (finished) plans and testing them against the criteria. Rather, planners developed the plans in an evolutionary manner by transforming the information presented in the problem statement using the representation on the planning board. Continually during the process of planning, planners seemed to be looking for ways of efficiently organizing and prioritizing the information they needed to consider so that a good solution would be discovered without overload of their limited processing and memory capabilities.

It took time for planners to develop ways of structuring and decomposing the problem. Methods for organizing the information and procedures for manipulating it were discovered and refined during the course of the sessions. For example, both planners decided to split the development of the plans for red and blue early in the planning procedure. They established ways to handle the spatial aspects of the plan (e.g., via representations of routes on the planning board) and the temporal aspects of the plan (e.g., by dividing the plan into phases

anchored on the transfer event). Further, they devised ways to co-ordinate the spatial and temporal aspects of plan development by, for example, the counting of ticks for the travelling of a route, and then the establishment of a transfer location. They discovered which information was critical for the viability of the plan (the rules concerning position of drinks and baked goods in the basket) and which was not. Furthermore they learned procedures to guide the order in which this information was considered.

There were a variety of planning strategies exhibited by planners. Some pertained to the best use of the environment available for planning (the planning board) at a somewhat mechanical level. The planners considered, for example, how to use the colored pencils; what codes should be used for marking items to be picked up; whether and how to annotate the number of ticks required for a route; when to take a second planning board. Some strategies pertained to choosing a good general criteria for a solution, thus guiding the top-down search for a plan. For example, both planners attempted to find a plan in which the red robot went as directly as possible from IN to OUT. More detailed strategies concerned, for example, the selection of the best pickup points (of two or three possibilities) to minimize, at a local level, the distance travelled by a robot. Unfortunately, subjects' verbal protocols did not often mention the strategies that they used, and so they need to be inferred. The issue of strategies for planning is a topic that should be investigated in more detail.

One factor that may have a significant influence on the way that planners structured their solutions to the planning problem is the manner in which they were trained in the first three sessions. In the training sessions, planners received three simpler problems that focussed on aspects of the more complex problem solved later. In the first training problem, planners dealt with only one robot; the second training problem used the first as a basis, and introduced the basket constraints; in the third, planners were required to co-ordinate two robots, but were not required to deal with the constraints. The specific substructuring of the planning problem suggested by the training sessions may have pre-disposed planners to decompose the more complex problem in the same way. Furthermore, in training, planners were already adopting strategies and methods for solving the more complex shopping problem. This study did not take account of these previously-developed approaches and strategies. We propose that a future experiment should focus on how people solve this planning problem without training.

Another important finding in this study was that planners attended to different levels of detail of information in planning. Furthermore, plans themselves seemed to be developed at different levels of detail. Sometimes, concepts used in planning were discussed at a gross level of spatial or temporal detail (e.g., the top and bottom of the store; before or after the transfer event); at other times, a relatively fine level of detail was manipulated (e.g., specific squares for the transfer of items, detailed ordering on their pickup). Our analysis identified

three levels of detail in planning. It would be useful to have this estimate confirmed, possibly by the planners themselves. The protocols further showed that there was a general progression from the use of gross information to the use of detailed information during the course of plan development. However, there was a great deal of variability in this progression as can be seen in the sample protocol.

Planning in this task was also characterized by repeated simulation of the proposed plan or plan fragments. A difficulty for planners in simulating execution stemmed from that fact that the two robots moved simultaneously; it was hard to keep track of where each was as the simulation proceeded. Planners resorted to simulating first the movement of one robot (for a short period of time) and then the other. The simulation of execution seemed to aid planners in clarifying the state of the robots at a point in time and in reviewing the final plan.

The product of the process of planning is the plan itself. It is the planner's mental concept of how the robots must move and carry out the pickup of items so that the goal is satisfied. It is what the planner intends should be executed. The planning board served as an a sort of extended memory for the planner, a place to record the plan so that it could be used to guide execution. Both planners formulated their final plan as two routes, one for red and one for blue, with the items to be picked up indicated. In addition to the plan itself, the planning process also resulted in intermediate products -- fragments of routes, partitions of items, proposed transfer areas -- that were manipulated in the process of planning. For example, partial routes for the robots were constructed by both planners and then manipulated (e.g., erased, annotated); potential transfer points were marked. These intermediate products could be considered working plans or working plan fragments. This study gave only an indirect indication of the planners' mental representation of plans and working plans. It is also possible that these representations were influenced by the planning environment in which the planners worked.

The planning environment (i.e., the planning board) provided a convenient way of representing the spatial aspects of the plan, and thereby the intermediate products of a spatial nature. It did not provide a convenient way of representing the temporal aspects of the evolving plan; planners seemed to have difficulty co-ordinating the two robots in time. The nature of planning environment has a major influence on the ease with which the intermediate products of planning can be represented, and thus may also have a considerable effect on the process of planning itself. In a sense, this influence is unavoidable; it is virtually impossible for planners to produce a plan for a problem as complex as this one is without some external way of representing and manipulating the concepts. It would be worthwhile to deliberately vary the planning environment to study the effect on the planning process.

We have mentioned that there are different degrees of detail of information considered in planning and that working or intermediate plans seem to be developed in varying levels of detail. Although it was not an overall characteristic of the plans developed in this study, it is also possible that the final plan for a particular problem might be developed to a lesser detail by one planner than another. In the paradigm chosen for this study, planners are not forced to plan to a certain level of detail per se. Nor are they under any time constraint. They are individually free to stop the planning phase and begin execution when they are satisfied with their plans. There is a tradeoff between effort devoted to planning, and thus the completeness of the plan, and the effort needed for execution. A planner could stop planning early, with a relatively incomplete plan, and devote extra effort "on the spot" during execution to making small changes or to developing further the details necessary for execution (actually a form of further planning). This kind of behavior was occasionally observed in this study. However, premature termination of plan development during the planning phase puts the planner at risk; it may turn out that the plan is not successful because all aspects and interactions had not been considered fully.

Occasionally, plans made by the planners in this study failed in some way during execution and replanning was necessary. It was not always clear whether the requirement for replanning resulted from a) incomplete planning during the original planning phase, resulting in the planner overlooking some critical detail; b) a error in planning, for example, a misconception about the way that robots behave in the store, or a miscalculation in timing; c) inadequate annotation of a plan that was, in fact, completely developed, resulting in faulty execution (e.g., the planner "forgot" to pick up an item, although intending to). This issue deserves further investigation.

Finally, it is noteworthy that the planners in this study did not deliberately consider alternative plans for solving a problem; typically they developed only one plan which was then executed. This is somewhat surprising, since the planners had no *a priori* criterion for judging the goodness of a particular plan (in terms of the number of ticks it cost); one might expect, therefore, that they would want to compare two or more different plans (for a given problem) in order to determine the one with the minimum number of ticks. Presumably, though, planners were satisfied with developing criteria for the goodness of the plan through feedback during its execution. Perhaps it cost too much cognitive effort for planners to develop and compare different plans for a problem. Limitations in the flexibility of the planning environment might also be a factor. The planning board did not facilitate backtracking in planning to permit consideration of alternatives. Furthermore, it was not easy for planners to store, recover and compare alternative plans.

Although this discussion has pointed to a number of characteristics of planning behavior, it should be emphasized that they are based on preliminary observations of only two planners.

4.2 Analysis method

The protocol analysis method adopted for this study permitted us to consider step-by-step the planners' processing of information during planning. The analysis carried out in this study resulted in the identification of a set of plan actions that describe most of the overt activities of the planners as reflected in the verbal and graphical protocols. In particular, the videotaping methodology and analysis of graphical interactions with the planning board permitted us to address the manipulation of spatial information that is a fundamental component of planning in this problem.

It is very likely that the plan action set for this problem is incomplete, since it was developed using only the protocols of two planners. Further studies with a wider range of planners will indicate whether it needs to be extended and refined.

One problem in using the plan action set for coding of concurrent verbal and graphical protocols is that it is often difficult to determine a unique code for each chunk of the protocol. In this study, chunking of the protocol for analysis was done by focussing on phrasing in the verbal protocol; the graphical protocol was then added alongside, in the form of an adjunct. However, at times the concurrent verbal and graphical protocols suggest that planners were executing planning actions simultaneously, for example, concurrent route creation (graphical) and assignment of items to be picked up by the robot (verbal). In these instances two codes have to be assigned. It is difficult to find a chunking of verbal+graphical that solves this problem, since the graphical protocol is closely coupled to the verbal; for example, it often also serves to clarify the deictic references (e.g., "this", "those") in the verbal protocol.

The analysis method was laborious and very time consuming, especially the coding of the graphical protocol. It required many iterations to develop the object and concept vocabulary and the plan action codes. Computer-based tools or an environment for handling and coding videotaped data of this sort would be very helpful in facilitating the coding process and ensuring its consistency.

A deficiency in the format developed for coding the protocols is that we have, as yet, no way of notating the intermediate states of the plan (the working plan/plan fragments) alongside the plan actions. A record of the state of the plan(s) as it has been developed by the planner to that point in the protocol could be helpful in uncovering errors in planning. We have experimented with one graphical notation system and will continue to search for a suitable notation system.

4.3 A hierarchical model for efficient planning

In this section, we propose a hierarchical model of planning for this task that takes account of the observations of planners' behavior made in conjunction with the analysis. However, the model is idealized, in the sense that it describes what we believe to be an "efficient" planning procedure, one that experienced planners might adopt. An efficient procedure for planning organizes the treatment of the problem and guides the search for a solution in a way that there is a high likelihood that a successful plan will have been found by the end of the procedure. A suitable organization (subdivision) of the problem is necessary because humans' limited cognitive processing cannot manage the full range of detail and interactions that needs to be considered simultaneously in planning problems of this kind. Thus an efficient procedure minimizes the work that the planner must do to create a successful plan for the range of circumstances expected. An efficient procedure does not guarantee that a successful plan will be created after a given amount of work, but it raises the probability that it will.

Hierarchical models of planning propose that the process of planning is tightly linked to a hierarchy of plan representations at different levels of abstraction (degrees of detail). In hierarchical planning, the planner creates increasingly more detailed plans in successive phases of the planning procedure. The hierarchical approach also advocates that in cases where the problem cannot be cleanly subdivided into independent subgoals, that a complete plan be produced at a given level of detail before planning at the next level of detail is started. Planning is continued until a plan of "sufficient" detail has been produced.

There is evidence from analysis of the protocols in this study that planning is carried out at varying levels of detail: three levels have been identified in the protocols, as described in a previous section.

The planning protocols show an identifiable sequence of steps that are followed in solving this planning problem. Planners seem to use a core procedure in which they:

1. Orient on the specific resources, rules and/or layout given in the problem statement;
2. Adopt a strategy for creating a plan or plan fragment, making deductions about necessary plan characteristics based on the analysis in step 1;
3. Create a working plan by applying specific and general strategies;
4. Evaluate the plan to ensure it satisfies all rules and constraints;
5. Decide whether to accept the plan; if not, go back to modify the working plan, or to create an entirely new plan.

Notes:

1. Steps in [] are optional
2. The diagram shows a standard sequence of steps for planning. Backtracking to previous steps can and does occur; however, only a portion of the backtracking pathways are shown.

PREPLAN

- Orient on problem requirements**
 - Note general problem requirements
 - Note resources and characteristics
 - Note criteria of solution
- Adopt general strategy for problem**
 - Deduce very general plan characteristics
- Transform representation of problem**
 - Mark items on layout

LEVEL 1 PLAN CREATION

- Orient on rules**
 - Note rules concerning drinks, baked goods, dairy
 - Translate rules for particular layout: specific items, spatial location
 - Make further transformation of representation
- Adopt strategy based primarily on rules**
 - Deduce plan characteristics from drinks rule/location
 - Deduce plan characteristics from baked rule/location
 - Deduce plan characteristics from dairy rule/location
- Create very rough Plan - P1**
 - Make/modify P1 for one robot
 - choose/modify very rough assignment/route
 - Make/modify P1 for other robot
 - Determine number of transfers needed (if any)
- [Evaluate P1]**
 - Check against rules
- ??Accept??**
- ??Enough detail??** y → **END**

continued...

Fig. 4 An efficient procedure for executing the planning task.

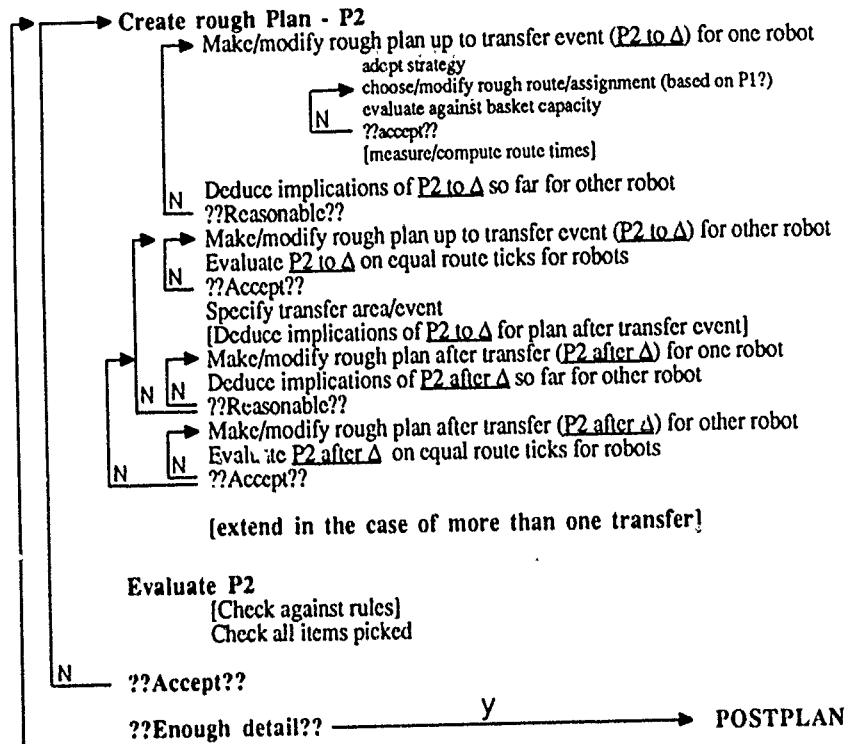
Figure 4: continued

LEVEL 2 PLAN CREATION**Orient on whole layout**

Form rough groups or partitions of items to be picked
Note any spatial "orphans"

Adopt strategy based on layout

Deduce plan characteristics from grouping of items



from LEVEL 3

Figure 4: continued

LEVEL 3 PLAN CREATION

Orient on relative location of items

Adopt strategy based on item location

Deduce plan characteristics from relative locations of items

Create detailed Plan - P3

Make/modify detailed plan P3 to Δ for one robot

adopt strategy
choose/modify detailed route/assignment (based on P2)
evaluate against basket capacity
[measure/compute ticks]
N ??accept??

Deduce implications of P3 to Δ so far for other robot

Specify potential transfer point

Make/modify detailed plan P3 to Δ for other robot

Evaluate P3 to Δ on equal route ticks for robots

N ??Accept??

Tune P3 to Δ on ticks

adjust transfer point or modify assignment/route
N ??accept??

Specify transfer

fix transfer point
fix number/type of items to be transferred

N Deduce implications of P3 to Δ on P3 after Δ

N ??Accept??

Make/modify detailed plan P3 after Δ for one robot

Deduce implications of P3 after Δ so far for other robot
measure no. remaining items

N Make/modify detailed plan P3 after Δ for other robot

Evaluate P3 after Δ on equal route ticks for robots

N ??Accept??

Tune P3 after Δ on ticks

N ??Acceptable??

[extend in the case of more than one transfer]

Evaluate P3

[Check against rules]

[Check all items picked]

Check total time satisfactory

N ??Accept??

POSTPLAN

Consolidate Plan

Join plan parts together

Redraw routes

Specify (mark) pickup points, route direction

Review entire Plan

Check all rules, conditions satisfied

Replay plan

END

This core procedure is invoked repeatedly during planning, and can be detected at both micro and macro levels.

By coupling the notion of levels of plan detail with the core procedure for planning described above, we can create a plausible model for efficient planning based on hierarchical, top-down development of the plan. The model is given in detail in Fig. 4. The model proposes that planning in the shopping problem is efficiently accomplished by proceeding through 5 phases:

- a) PREPLAN,
- b) LEVEL 1 PLAN CREATION,
- c) LEVEL 2 PLAN CREATION,
- d) LEVEL 3 PLAN CREATION, and
- e) POSTPLAN.

Each phase has a number of steps associated with it, that are themselves broken out into substeps at two further levels. Thus the process itself is described hierarchically. The core activities of orientation, adoption of strategy, create plan, and evaluate (and possibly modify) occur three times, against three levels of detail of information resulting in plans of increasing detail (P1, P2, and P3). At the end of each phase of PLAN CREATION, the planner has the option of terminating plan development if it is felt that the level of detail is sufficient (at the step ??Accept??), in which case subsequent plan creation phases are bypassed. The diagram suggests that PLAN CREATION is carried out as a linear sequence of major steps in which first, a rough plan is created; and then, two more plans of increasing detail based on that initial rough plan are created. However, backtracking to PLAN CREATION at the previous level of plan detail can and does occur when the plan developed at the higher level of abstraction proves to be unworkable at the next lower level.

Prior to the phases of PLAN CREATION is a phase of PREPLAN, where the planner "sets up" for the problem, noting general problem requirements and resources, adopting some general approach to planning (e.g., using the colored pencils to draw routes) and doing other preparatory work like marking the items to be picked up on the layout of the store. There is also a POSTPLAN phase which serves as preparation for execution of the plan: plan fragments are consolidated and ordered, a final check is made that the rules are satisfied and the plan may be replayed in its entirety. The plan on the board is often annotated in more detail to ensure correct execution.

Let us consider now the actual Create Plan step that itself forms the kernel of activity in each level of PLAN CREATION. In Level 1, this step is short, and consists most often of simply making a very gross partitioning of the items between robots, or selecting rough routes for each robot to follow. A key step is to determine whether or not a transfer is needed.

At the next level of plan detail, Level 2, plan creation is guided by the plan developed at Level 1. The transfer event, if it has been proposed, plays an important role in structuring the process. The planners were observed to first make a rough plan for one robot up to the transfer event (denoted as $\langle ! \rangle$ in the figure), that is, to select an assignment or routing for one robot. Often the assignment/routing is checked to ensure that it does not exceed the basket capacity of the robot, and sometimes a rough estimate is made of the cost (in ticks) of a proposed route. In the next step, the implications of this selection for the other robot are deduced (i.e., Can a second route be chosen that puts the second robot in about the same location as the first at the time of the transfer event?) If the implications are found to be "reasonable", in the sense that the planner believes that a compatible second route can be (easily) found, the rough plan up to the transfer event is then developed for the second robot. At this stage, the rough plan (P2 to Δ) is evaluated to see whether the lengths of the routes for the two robots are equivalent in time. If they are equivalent, this prompts the fixing of an approximate location for the transfer. If not, the planner backs up to modify one or the other route to try to balance the two.

Once the rough plan for the two robots has been developed up to the transfer event, the same set of steps occurs for plan development after the transfer (and can be extended in the case of more than one transfer). Backtracking to a prior step of plan development occurs within this set of steps too, but the backtracking can also send the planner back to re-consider the first part of the plan, that part up to the transfer point. Note that the model is not dependent upon the existence of a transfer event. If a transfer has been proposed in LEVEL 1, it provides a convenient point for subdividing the planning at LEVEL 2. However, if no transfer has been deemed necessary, then Create Plan P2 addresses the whole route for one robot at a time, rather than two route fragments split at the transfer.

The procedure for Create Plan P3 is basically the same, except that the P2 plan is used as a basis for P3 and more detail is taken into account. For example, the model proposes that planner works item by item in assignment to robots, and square-by-square in route development. The transfer is specified in detail. Also, there can be an extra step of "tuning" of one robot's workload/route to the other by small adjustment of the assignment or routes. Backtracking in the case of an unacceptable evaluation of the evolving plan also occurs within this phase. More major backtracking may also happen if the planner decides that P3 cannot be satisfactorily modified. In this case the planner goes back to Level 2 to modify or re-create P2 and then re-plans at Level 3.

Focussing now on larger chunks of the procedure, let us consider the differences between LEVEL 1, LEVEL 2 and LEVEL 3 PLAN CREATION. One difference is simply the degree of detail of information exploited in planning at the different levels: the least detail is used at LEVEL 1 and the most at LEVEL 3. However, by LEVEL 3 the plan is already partially structured by virtue of work

at previous levels of planning, and the plan itself has been divided into segments that correspond to steps in the procedure. So the planner is dealing with approximately the same amount of planning information in each step. There is another difference pertaining to the nature of the information during the Orientation and Adopt Strategy steps. In LEVEL 1, an efficient procedure calls for a focussing primarily on a plan that satisfies the basket rules; they have the highest priority, since they must not be violated. In the next level, LEVEL 2, efficient planning focuses on ensuring pickup of all items (whilst not violating the rules). In the last level of planning (P3), attention can be given to optimizing the routes of the two robots in an attempt to minimize the number of store clock ticks needed. This is the least critical of all the problem requirements, since no absolute "standard" in this regard is given in the problem statement.

Finally, it is possible for the procedure to be short-circuited from either LEVEL 1 or LEVEL 2 PLAN CREATION if the planner feels that enough plan detail exists for satisfactory execution. If planning is terminated after LEVEL 2, the planner may go to a short phase of POSTPLAN, for rough consolidation of the plan. However, if the planning is terminated after LEVEL 1, the planner cannot do a review, because the plan has not been annotated in enough detail to be checked.

The form of the model suggests that planning in this task is a linear procedure that is carried out neatly step-by-step. In some cases (e.g., for experienced planners, for relatively easy problems) this may be true. In most planning, though, we expect that there will be at least some backtracking, as the planner discovers that previously developed parts of the plan need to be modified. In principle, backtracking from any step to any other step could occur. We expect, however, that certain backtracking pathways are more frequently followed. These have yet to be determined. Of even greater interest are cases in which backtracking in the procedure occurs because of cognitive overload. For example, the planner may forget an earlier plan fragment and need to go back to re-create it; or the planner may make an error in planning that causes backtracking.

The model provides a basis for further study of this planning problem. In future experiments we will test the model against subjects' planning procedures, with the focus particularly on comparing early planning procedures with those adopted later in a sequence. Special attention will be given to the conditions under which backtracking occurs.

5. CONCLUSIONS

The SPLITS planning problem and paradigm of plan/execute enabled us to evoke human planning behavior in a controlled way and capture it on videotape. From the verbal and graphical protocols we were able to identify a set of primitive planning concepts and actions used by planners in carrying out the planning task. A method for coding protocols was also developed; this scheme will be used in the analysis of future experiments.

Observations of planners' behavior in this study indicated that plans were developed in an evolutionary manner. Planners discovered and refined methods for organizing the information and procedures for manipulating it during the course of the sessions. Furthermore, planners attended to different levels of detail of information in planning, and used a variety of planning strategies. Planners usually planned to a level of detail sufficient for execution, although there were several instances of replanning.

A hierarchical model for efficient planning for this task has been developed. The model proposes that planning is executed in a top-down manner with the planner focussing on increasingly detailed objects and concepts as planning proceeds. A future experiment will test the model to determine the degree to which human planning behavior conforms to this hierarchical approach.

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Soesterberg, August 7, 1991

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REPORT DOCUMENTATION PAGE

1. DEFENCE REPORT NUMBER (MOO-NL) TD 91-2171	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER IZF 1991 B-11
4. PROJECT/TASK/WORK UNIT NO. 733.2	5. CONTRACT NUMBER B91-35	6. REPORT DATE August 7, 1991
7. NUMBER OF PAGES 51	8. NUMBER OF REFERENCES 5	9. TYPE OF REPORT AND DATES COVERED Final
10. TITLE AND SUBTITLE Human Cognitive Processes in Command and Control Planning. 3: Determining Basic Processes involved in Planning in Time and Space		
11. AUTHOR(S) C.A. McCann and P.J.M.D. Essens		
12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) TNO Institute for Perception Kampweg 5 3769 DE SOESTERBERG		
13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) TNO Defence Research Schoemakerstraat 97 2628 VK Delft		
14. SUPPLEMENTARY NOTES		
15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE) This study investigates how people create plans to accomplish a task that has both temporal and spatial components. The study had two goals: to develop a method for determining the cognitive processes associated with planning; and to develop a model for efficient planning for the task used in the study. Two planners gave verbal and graphical protocols while planning the most efficient way for shopping robots to pick up commodities in a grocery store. Each planner created a plan for twelve such problems and the plan was executed after each planning session. The protocols were analyzed to identify the primitive concepts and actions used in the planning process. Observations of planners' behavior in this study indicated that plans were developed in an evolutionary manner. Planners discovered and refined methods for organizing the information and procedures for manipulating it during the course of the sessions. Furthermore, it was shown that planners attended to different levels of detail of information in planning, and used a variety of planning strategies. A hierarchical model for efficient planning for this task is proposed that assumes plans are developed hierarchically at three successive levels of detail.		
16. DESCRIPTORS Command and Control Problem Solving		IDENTIFIERS Military Planning Protocol Analysis Cognitive Task Analysis
17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
18. DISTRIBUTION/AVAILABILITY STATEMENT Unlimited availability		17d. SECURITY CLASSIFICATION (OF TITLES)

VERZENDLIJST

1. Hoofddirecteur van TNO-Defensieonderzoek
2. Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie
3. {
Hoofd Wetenschappelijk Onderzoek KL
Plv. Hoofd Wetenschappelijk Onderzoek KL
- 4, 5. Hoofd Wetenschappelijk Onderzoek KLu
6. {
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gevraagd door tussenkomst van de HWOs of de DWO.