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Partial and total-order planning: evidence from normal and prefrontally damaged populations

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Abstract

This paper examines human planning abilities, using as its inspiration planning techniques developed in artificial intelligence. AI research has shown that in certain problems *partial-order planners,* which manipulate partial plans while not committing to a particular ordering of those partial plans, are more efficient than *total-order planners,* which represent all partial plans as totally ordered. This research asks whether total-order planning and/or partial-order planning are accurate descriptions of human planning, and if different populations use different planning techniques. Using a simple planning task modeled after tasks designed in artificial intelligence we tested 7–8 year-old children, 11–13 year-old children, adult controls, and adults with damage to the prefrontal cortex. We found that adults and older children exhibited performance on planning tasks of varying complexity which matched that of artificial partial-order planners, and that this pattern of performance did not vary with multiple presentations of the planning task. In contrast, young children and adults with damage to the prefrontal cortex exhibited performance matching that of artificial total-order planners. This pattern of performance did vary, however, with multiple presentations of the planning task, with the young children and adults with cortical damage displaying aspects of total-order planning. In a further study we found that adolescents who had sustained damage to the prefrontal cortex as children displayed two

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different patterns of performance; when measures of reaction time were analyzed they revealed a pattern of performance suggestive of partial-order plan representations. However, analyses of the adolescents' protocols revealed a pattern of performance suggestive of total-order plan representations. The significance of these results to psychology, neuroscience, and artificial intelligence are discussed.

Keywords: Planning; Frontal lobe; Brain damage

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1. Introduction

Planning is a common daily activity–we plan our day, we plan our vacation, we plan our children's lives. However, despite its ubiquity, planning is not a simple task. Planning, as an activity, includes aspects of memory, problem solving, representations, sequencing of representations, and goal-directed behavior. The complexity of planning is evident when the planning abilities of special populations, most notably children and adults with damage to the prefrontal cortex, are examined. Research examining these populations have found differences between the planning abilities of young children and those of older children and adults, with the younger children showing rigid, inflexible planning and adults and older children showing flexible, opportunistic planning (Hayes-Roth & Hayes-Roth, 1979; Pea & Hawkins, 1987). Similar inefficiencies in the planning of adults with damage to the prefrontal cortex have been also been noted by Grafman (1989, 1995) and Shallice (1988). However, despite the variety of research examining planning skills in children, adults, and adults with prefrontal damage, there has not been a comprehensive investigation of the planning abilities across these very different populations. That is our goal in this research.

To reach this goal we have taken as our inspiration a set of problems developed in the field of artificial intelligence. AI research has shown that in certain problem domains *partial-order planners* are more efficient than *total-order planners.* Total-order planners construct a linear, *total plan* to achieve a goal. In contrast, partial-order planners construct *partially ordered partial plans* that are then manipulated to produce the final, correct plan. Partial-order planning does not commit to a particular ordering of partial plans, and, unlike total-order planning, avoids making decisions which may need to be revoked later. AI research has shown that in certain domains partial-order planners are more efficient than total-order planners. These domains include the artificial D^1S^1 problem domains (in which the completion of one action deletes the precondition of a previous action) studied by Barrett and Weld (1993) (See also below.) and presumably many real-world problems with similar structures. One of the goals of this research is to determine whether total-order planning and/or partial-order planning are accurate descriptions of human planning, and further, if different populations use different planning strategies. We will begin with a description of the planning literature in adults, children, and brain-injured adults, followed by a brief discussion of the problem domain developed in artificial intelligence planning research, and a discussion of why these specific problems are appropriate for this work.

1.1. Planning across different populations

1.1.1. Planning in adults

Planning is generally defined as the process of formulating a sequence of operations intended for achieving some goal (Hayes-Roth & Hayes-Roth, 1979; Pea, 1982; Miller, Galanter & Pribram, 1960; Rogoff, Gauvain & Gardner, 1987; Scholnick & Friedman, 1987). The representation of this sequence is called a plan. This plan can be represented internally (in the planner's mind) or externally (e.g., a blueprint, a travel route, a "to do" list).

Hayes-Roth and Hayes-Roth (1979) provided one of the first empirically based models of the planning process in humans. They proposed that human planning is largely opportunistic; at each point in the planning process the planner's current decision affects opportunities and decisions later in the development of the plan. The planner then follows through on these opportunities. Plans grow incrementally as each new decision is incorporated into, and revises, previous decisions. Thus, planning is a multidirectional revisionary process.

Hayes-Roth and Hayes-Roth used participants' performance in a simple planning task to provide empirical support for their position. Participants were asked to formulate a plan which would accomplish a series of errands in a set amount of time. They had access to a map of a hypothetical town and a list of various chores to be completed, along with the priority of each chore. The participants did not actually perform these errands; rather, they were asked to indicate which errands they would do, the order in which they would do them, and the route they would use to travel between each location on the map. Their verbal protocols were recorded and later analyzed for the presence of planning clusters. The following is an example of part of a protocol (italics added):

"[7] The appliance store is a few blocks away. The medicine for the dog at the vet's office isn't too far away. Movie theaters-let's hold off on that for a little while. Pick up the watch. That's all the way across town. Special order a book at the bookstore.

[8] Probably it would be best if we headed in a southeasterly direction. Start heading this way. *I can see later on there are a million things I want to do in that part of town*

[9] No we're not. We could end up with a movie just before we get the car. *I had thought at first that I might head in a southeasterly direction* .... However, near my parking lot also is a movie, which would make it convenient to get out of the movie and go to the car. But I think we can still end up that way (Hayes-Roth & Hayes-Roth, 1979, p. 278)."

Note that in this excerpt the participant begins by listing the first errands he sees near his starting point (7). However, he then begins to "cluster" the errands by location, planning to proceed to the southeast section of town and, once there, continue to formulate his plan (8). In effect, the participant is forming partial plans to be implemented and integrated later. Next, he modifies this strategy and decides to change directions based on the integration of further information (9). The participant then modifies his plan accordingly, operating in an "opportunistic" fashion. This model became the standard for many researchers of this type of planning (e.g., (Dreher & Oerter, 1987; Gauvain & Rogoff, 1989; Pea & Hawkins, 1987)).

Opportunistic planning, as described by Hayes-Roth and Hayes-Roth, displays many of the characteristics of partial-order planning; partial plans are formed and revised as new pieces of information are considered. This similarity to computational simulations of planning suggests that, like some computational models, in some domains the use of partial-order plans is an efficient planning strategy, and further, that this type of planning is often used by adults.

1.1.2. Planning in children

Research of adult planning suggests that the use of malleable, opportunistic planning is the most efficient, and according to Hayes-Roth and Hayes-Roth (1979), the most valid description of the planning process. How then does this ability develop, and is the use of flexible, opportunistic planning constant across age?

One view of children's planning proposes that the ability to flexibly form and modify plans develops as children develop. Pea and his colleagues (Pea, 1982; Pea & Hawkins, 1987) performed an experiment in which two groups of children (8–9 year-olds and 11–12 year-olds) were given a chore-scheduling task to perform using a Plexiglas representation of a classroom. The children were given a list of six chores to complete in the "classroom," some of which had other prerequisite chores which had to be completed before the chore could be executed (e.g., the water can had to be obtained before the plants could be watered). The children were instructed to plan the most efficient route to complete all of the chores. Analysis of planning performance and verbal protocol revealed that the older group of children made more "high level" (executive control and metacognitive) decisions than did the younger children. Their analysis also revealed that high level decisions were associated with flexible and efficient plans. Pea and Hawkins proposed that this flexibility allowed the planner to avoid committing to one full plan too early, enabling her to adapt to unexpected circumstances later in the planning process.

A similar view proposes that older children possess the ability to adapt to the type of planning to be performed (Gauvain & Rogoff, 1989; Rogoff et al., 1987). When advance planning is necessary, older children will form complete plans. However, when the planning domain allows for it, older children will produce flexible, opportunistic plans. Younger children, in contrast, will often lack the ability to integrate new information into their plan, or will be unable to coordinate subgoals to reach a goal, and thus will be unable to respond flexibly (Rogoff et al., 1987).

As with adults, the flexible opportunistic planning of the older children suggests the use of partial-order planning; partial plans are formed and modified according to the demands of the task situation. Further, the nonflexible planning of the younger children suggests the use of total-order planning; total plans are formed by the child and they are unable, or unwilling, to deviate from these plans. This similarity to computational simulations of planning suggests that computational models of planning could serve as a useful guide when investigating planning in children and adults.

1.1.3. The neuropsychology of planning

Neuropsychologists have long studied the role of the frontal cortex in human behavior, and in particular, the effects of damage to this area of the brain. It has long been known that patients with frontal lobe lesions will often behave inappropriately in social situations, experience radical mood swings, and display deficits in processing temporal relationships and order. These deficits appear despite seemingly normal abilities in language, perception, verbal expression, memory, and attention (Grafman, 1989, 1994). In addition to the previously described deficits, it has also been proposed that these patients experience deficits in planning and problem solving (Grafman, 1989; Shallice, 1988). Note, however, that patients with frontal lobe lesions may fail on planning tasks for a variety of reasons, such as perseveration, inattentiveness, and sequence errors. Although cognitive neuroscience research has provided abundant evidence suggesting that the prefrontal cortex is important for maintaining and manipulating information over time, the majority of neuropsychological models fail to explicate the precise role of the frontal cortex in cognitive processes (Grafman, 1989). The models also rely on evidence that was obtained from working memory tasks that are not directly related to planning development or execution. One of the goals of our experiment is to provide direct evidence for the role of the frontal cortex in planning behavior, and specifically, to show that damage to the frontal cortex will lead to deficits in the patient's ability to form and carry out complex plans.

The cognitive neuroscience research literature also motivated our choice of participant populations. Specifically, it has been suggested that many of children's cognitive abilities are maturationally based (e.g., Case, 1992, Halford, 1993), and further, that it is neurological development, specifically development of the frontal lobe, that determines the pace of children's cognitive development (Diamond, 1993; Goldman-Rakic, 1987). If this is the case, then one explanation for young children's inability to form flexible plans may be a lack of frontal lobe maturation. To take the logic one step further, if in fact deficits in planning are due to deficits in the frontal lobe, a comparison between immature and damaged populations would be particularly revealing. Consequently, we chose to test children at two different levels of maturation – children aged seven to eight years, old enough to perform the Chores task, but theoretically not fully mature, and eleven to twelve year-olds who are on the edge of the hypothesized transition between neurological immaturity and maturity.

1.1.4. Planning in artificial domains

As we note previously, the problem set chosen for these experiments is based on work done in the field of artificial intelligence, where much work has been done on the differences between partial-order and total-order planning systems. This work is based on systems which were developed to utilize nonlinear planning (McAllester & Rosenblitt, 1991; Sacerdoti, 1975), and involves the representation of action routines as partial orders instead of representation of total orders. This type of representation means that partial plans may be constructed, thus avoiding commitment to a particular ordering of subgoals. The order in which subgoals are to be achieved is determined by analysis of the possible interactions between partial plans for different subgoals. Through the use of partial-order plan representations, this analysis is delayed as long as possible, thereby minimizing the chances that the planner will later have to revoke ordering decisions (Sacerdoti, 1975). As a result, computation of plans may in many cases be more efficient than when total-order plan representations are used (Barrett & Weld, 1993).

Barrett and Weld (1993) examined the advantages and disadvantages of partial- and total-ordered planning algorithms in several problem domains. They developed three planning programs which utilized STRIPS-like operator schemata. A STRIPS operator (or action) schema consists of a *precondition list* containing items that must be true for the action to be performed, an *add list* containing items that are made true by the performance of the action, and a *delete list* containing items that are made false by the performance of the action (Fikes & Nilsson, 1971). Two of these programs, POCL (Partial-Order Casual Links) and TOCL (Total Order Casual Links) represented similar programs whose major differences were in their use of either partial-order or total-order representations respectively. Both programs were tested on several planning problems and their run times were analyzed.

In order to explain the performance differences of the different programs, Barrett and Weld extended Korf's (Korf, 1987) taxonomy of subgoal collections to include the categories *trivially serializable* and *laboriously serializable.* A set of subgoals was defined as trivially serializable if "each subgoal [could] be solved sequentially in any order without ever violating past progress (Barrett & Weld, 1993, p. 3–4)." A set of subgoals was laboriously serializable if "there exist[ed] an inadequate percentage of orders in which the subgoals may be solved without ever violating past progress (Barrett & Weld, 1993, p. 4)." They proposed that different plan representations would generate different search spaces, and could therefore yield trivially, laboriously, or completely nonserializable subgoal collections for the same problem.

Barrett and Weld tested these programs on problem domains named DxSy, where there were x entries in the delete set of each operator and y steps were required to achieve a given subgoal. One domain of particular interest was D^1S^1. In D^1S^1, each operator deletes the precondition of the operator which must immediately precede it. Therefore, there is only one possible correct sequence of operators for any D^1S^1 problem.

Observations of POCL and TOCL in this and several other problem domains led them to the conclusion that "Assuming that a problem's subgoals can be achieved in constant time, the expected time to solve a problem rises linearly with the number of subgoals if the problem is trivially serializable, but rises exponentially if the problem is laboriously serializable or nonserializable (Barrett & Weld, 1993, p. 36)." Runtime in D^1S^1rose linearly with the number of subgoals for POCL and rose exponentially with the number of subgoals for TOCL. This suggests that while partial-order planners require only linear time (dependent on the number of subgoals), total-order planners require exponential time.

1.2. The present work

The present work on planning is inspired by the work of Barrett and Weld (1993) in which they found that in the D^1S^1 domain the use of partial-order plan representations is more efficient (producing linear run times) than the use of total-order plan representations (producing exponential run times). We are attempting to apply these findings to planning in humans. To do this, we are presenting participants with problems from the D^1S^1 domain and, using reaction time as an analog to CPU run time, examining the use of total-order and partial-order plan representations in humans. Due to differences in memory capacity and processing speed between our human participants and an AI based planner, we do not expect that the planning of our human participants will be exactly like that of an AI based planner. We do, however, expect that some of the same limitations that apply to planning in AI will also apply to planning in humans. These predictions are based on our assumption that the representations of plans in artificial and in human planners share some commonalities.

Consequently, we predict that the shapes of the functions formed by the reaction times of our human participants will mirror the shapes of the CPU times found by Barrett and Weld when they compared total-order and partial-order planners.

Thus, the present line of research on human planning in the D^1S^1 domain (see Spector & Grafman, 1994) examines the plan representations of humans and their similarity to artificial planners. Although several researchers have proposed models which suggest that humans engage in something akin to partial-order planning (De Lisi, 1987; Hayes-Roth & Hayes-Roth, 1979; Klahr & Robinson, 1981; Kreitler & Kreitler, 1987; Pea & Hawkins, 1987), none have tested for it explicitly. Preliminary tests have suggested that adults do in fact use partially-ordered plan representations under certain conditions (Spector, Rattermann & Prentice, 1994; Spector, Rattermann, Prentice & Juneau, 1994). We questioned whether children's plan representations would reflect a less efficient form of partial-order planning, total-order planning, or something altogether different.

In order to investigate this, we utilized the Chores software for planning experiments (Spector & Grafman, 1994). Chores is a computer program which displays a map of a hypothetical town similar to that of previous errand-planning/chore-scheduling experiments (Dreher & Oerter, 1987; Hayes-Roth & Hayes-Roth, 1979; Kreitler & Kreitler, 1987; Pea & Hawkins, 1987). A participant is seated in front of a computer and given instructions for a "game" in which she must travel to different locations on the map using either the arrow keys or the mouse, collecting items at each of these locations. The items to be "acquired" at each location are displayed on a list beside the map, as are the items that the participant already possesses. An "Item Information" screen, which lists all the locations and the relationships between the different items to be acquired, can be accessed by clicking on an icon also displayed beside the map. The Chores map can be configured to any layout of locations, and these locations can contain any number of items. Constraints that are directly analogous to the constraints embodied in STRIPS operators can also be placed on each location. If a constraint is violated the participant is notified and she has the opportunity to press an "undo" key which negates previous moves in order to repair faults in her plan. More information regarding the specific details of the Chores interface will be presented later.

We configured the Chores experiment to reflect the D^1S^1 problem space (i.e., each place/operator had exactly one item in its delete set that deleted the precondition of its predecessor). Based on research suggesting that adults, like partial-order planners, exhibited linear time increases with an increasing number of subgoals (Spector, Rattermann & Prentice, 1994; Spector, Rattermann, Prentice & Juneau, 1994), we constructed four D^1S^1 trials with 2, 3, 4, and 5 subgoals respectively.

1.3. Total-order and partial-order planning in chores

Based on Barrett and Weld's (1993) findings in the D^1S^1 problem space, we predict that total-order planners will show an exponential increase in reaction time as the number of Chores increases, while partial-order planners will show a linear increase in reaction time as the number of Chores increases. These predicted patterns of behavior can be seen in the following examples. As noted previously, we have configured the Chores experiment to reflect the D^1S^1 problem space in which a visit to each location on the map requires one item

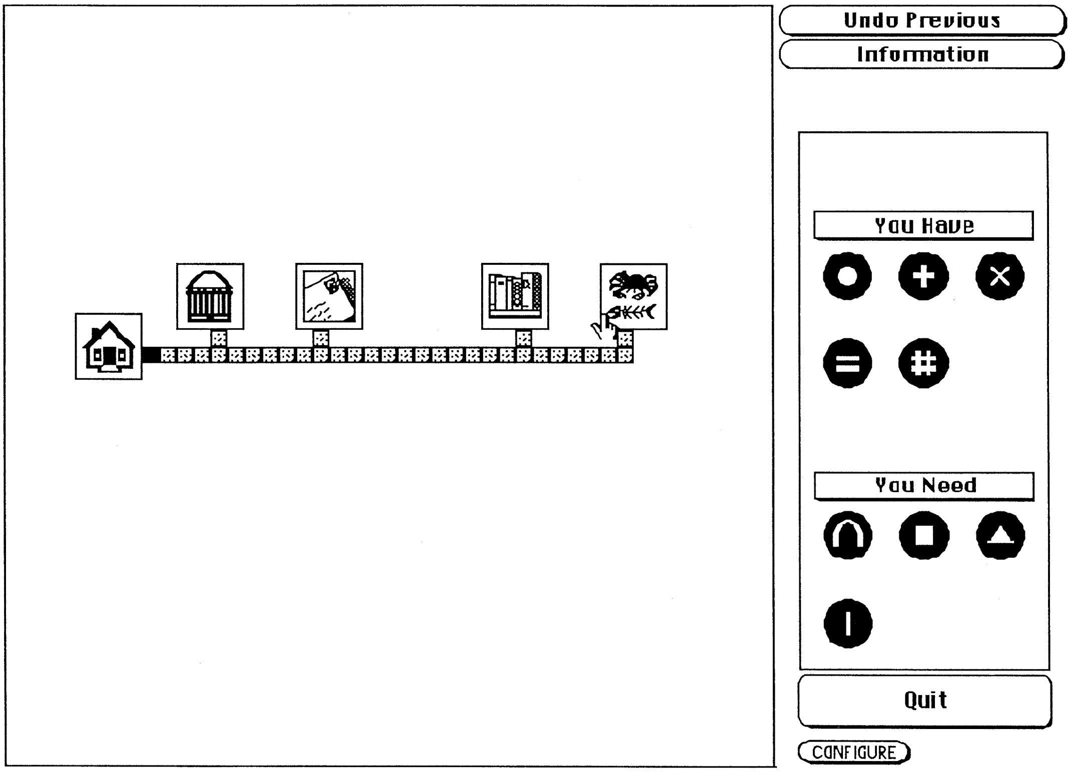

Fig. 1. Sample display from the Chores map.

and deletes the item needed to visit the previous location. A schematic of the four Chores problem used in this experiment follows. In this example, as in the experiment, the items to be acquired are abstract geometric shapes. (In the following example the Chores locations are placed in the correct order from left to right, while in the actual experiment these locations were scattered across a map of a hypothetical city (See Fig. 1.)) As the task begins the participant already possesses the "Equals" and the "Circle" as well as the "X" which is the precondition for entry into the library.

Location:	Library	Fish Market	Post Office	Museum
Precondition:	X	Equals	Circle	Hashmark
Deletes:	Plus	X	Equals	Circle
Adds:	Arch	Vertical Bar	Triangle	Square

A participant using total-order plans would proceed through this task by first designing a linear plan that determines the order in which all four chores will be performed. This plan can be designed before execution, or can be interleaved with execution—what is crucial is that it the participant is manipulating a representation of the entire plan. Thus, a hypothetical participant using total-order plans could attempt to solve the four Chore problem by moving to the Library, followed by the Fish Market, the Museum, and then the Post Office. Upon reaching the Post Office she would be notified of an error (the Circle, which was the precondition for the Post Office, was deleted when she went to the Museum) and would then have to form a new total-order plan, a process which entails manipulating all four locations before continuing. She could also use the "undo" key, in which case, due to the rigid nature of her plan, she would probably "undo" back to the beginning and form another total-order plan. Hence the exponential nature of her performance. Note that this is a characterization of a total-order planner's performance. We do not assume that an intelligent planner would continually ignore the information about ordering constraints learned during the execution of this task, and a total-order planner could incorporate information regarding the correct ordering of the Chores into her next plan representation. The crucial point is that this information will be incorporated into another inflexible total-order plan.

A participant using partial-order plans would divide the Chores task into flexible partial-order plans that can be manipulated and reordered without committing to a single inflexible plan. Thus, a characterization of a partial-order planner's performance would be to represent a plan to move to the Library, followed by the Fish Market. After executing that plan, the participant would form a further partial plan to move to the Museum and finally, the Post Office. While executing this plan, the participant is notified of an error when trying to enter the Post Office (like the total-order planner, he had also deleted the Circle when entering the Museum). The partial-order planner would then only have to manipulate the two partial plans remaining (by using the "undo" key), form another partial plan, and then execute it. This partial-order planning leads to the predicted linear increase in reaction time.

It is important to note that both the total-order and the partial-order planner will eventually reach a solution and could, in fact, reach this solution in the minimum number of moves. Further, both partial-order and total-order planners can interleave planning and action —the crucial difference for our experiment is the type of plan representations used to finally reach the solution— either total-order or partial-order. The different planning representations will manifest themselves in the behavioral measures observed, the most obvious being the participants' total-time to complete the Chores. However, because both planning and execution are included in the total time to completion, we also analyzed the time spent viewing the item information screen as a measure of pure planning. Finally, to examine any differences in the pattern of errors made by the participants as they performed Chores we analyzed the use of the "undo" key.

We have specific predictions regarding each of these measures. First, we predict that the use of total-order planning will cause an exponential increase in both time spent planning and in total time to complete this task. As with computer models, planning time will increase exponentially as the number of chores increases for total-order planners. This will be reflected in both total time to complete the chores and in time spent viewing the "Item Information" screen. The exponential increase in time to completion will be due to both the planner's inefficient use of the "undo" key— backtracking to the beginning and then unnecessarily repeating steps—and/or in time spent planning as they attempt to form a total plan with a large number of chores. Partial-order planners, in contrast, will be efficiently using the "undo" key –only backtracking to the beginning of the current partial plan– and will spend less time planning because they are forming partial plans made up of fewer chores. Thus, an increase in the number of chores will lead to a linear, not exponential, increase in time spent planning.

Our second measure is the pattern of errors displayed by our participants, and specifically, how the participant uses the “undo” key. We predict that both total-order and partial-order planners will use the “undo” key when confronted with a constraint violation. In this situation, total-order planners, because of the rigid nature of their plan representations, will be forced to “undo” the total plan and backtrack to the beginning before forming a new total plan. Partial-order planners, because of their flexible partial plans, will only backtrack to the beginning of the current partial plan before forming a new partial plan.

1.3.1. Populations of interest

In addition to investigating planning in adults, we were also interested in planning in populations that, based on current literature, could be assumed to have planning deficits–specifically, children and adults with damage to the prefrontal cortex. Developmental models of planning suggest that young children cannot utilize complex planning strategies (Klahr & Robinson, 1981; Pea, 1982; Pea & Hawkins, 1987). We wondered what planning strategies young children did use, and if they might be similar in performance to that of total-order planning systems. We also conjectured that adults with damage to the prefrontal cortex might show planning strategies similar to those shown by the children tested.

In Experiment 1 we tested two groups of children (6–8 year-olds and 11–12 year-olds) on a set of D^1S^1 tasks, modified slightly to make them appropriate for young children. We also tested a group of adults with damage to the prefrontal cortex and a group of normal adult controls on the original D^1S^1 tasks. We hypothesized that normal adults would show linear trends characteristic of total-order planning in the D^1S^1 domain, while young children, and possibly adults with prefrontal cortex damage, would exhibit exponential trends characteristic of total-order planning in the D^1S^1 domain. The performance of the 11–12 year-olds is more difficult to predict based on the available literature; we hypothesized, however, that they would exhibit the linear performance of a partial-order planner, while taking more time than the adults. Note that while linear or exponential performance would not conclusively indicate that the participants were forming partial- or total-order plan representations per se, they would indicate planning strategies similar in efficiency to these types of representations. Also, when this data are combined with other convergent measures from this experiment (described in the Methods section), we are provided with a comprehensive picture of planning in these populations.

2. Experiment 1

2.1. Method

2.1.1. Participants

Twelve adult control participants, eleven adults with damage to the prefrontal cortex, and sixteen children were tested in this experiment. The adult participants tested were between the ages of 20 and 63 years (6 males and 6 females) and were recruited from the general

Table 1
Characteristics of the adults and adolescents with damage to the prefrontal cortex

Participant	Gender	DOB	Education[A]	Handedness	VIQ	PIQ	Lesion[B]	Date of lesion
Adults								
1	M	6/6/49	14	R	105	95	B	VIETNAM
2	M	8/7/48	14	R	95	115	R	VIETNAM
3	M	3/25/47	12	R	86	83	B	VIETNAM
4	M	6/23/45	16	L	125	117	R	VIETNAM
5	M	3/28/45	16	R	101	104	R	VIETNAM
6	M	4/18/41	10	R	93	98	R	VIETNAM
7	M	3/22/48	14	R	96	118	B	VIETNAM
8	M	7/22/47	14	R	91	98	R	VIETNAM
9	M	1/15/46	12	L	102	102	L	VIETNAM
10	M	5/20/45	12	R	93	94	B	VIETNAM
11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Adolescents								
1	M	7/18/81	8	R	87	90	L	9/13/87
2	F	5/2/85	5	R	110	89	L	1/6/95
3	M	10/22/83	6	R	110	99	B	5/90
4	M	3/1/82	7	R	117	73	B	2/12/90
5	F	8/20/83	7	R	108	108	L	7/22/86
6	F	9/17/82	7	R	89	90	R	4/25/85
7	M	8/11/82	8	R	104	94	B	4/29/95
8	F	8/20/82	7	R	93	104	B	8/19/91
9	F	7/21/82	8	R	94	83	B	1/30/93

[A] Years of schooling.

[B] L = Left, R = Right, B = Bilateral.

population in the Bethesda, Maryland area. See Table 1 for a brief overview of the adults with damage to the prefrontal cortex, and the Appendix for a fuller description.

Eight children between the ages of 6–8 years (5 males and 3 females) and eight children between the ages of 11–12 years (4 males and 4 females) were recruited from the general population of the Amherst, Massachusetts area. All participants were Caucasian and from a middle class background. Both the adults and the children were paid for their participation.

2.1.2. Materials

Materials consisted of the NINDS/NIH Chores experiment developed by Lee Spector. The Chores experiment is a HyperCard stack for conducting psychological experiments related to planning-oriented cognitive tasks. We used two versions of the Chores software in this experiment; an initial version was used to test the adults while a modified version was used to test the children in this experiment and all of the participants in Experiment 2. There were no major changes made to the function or layout of the Chores software from the initial version to the modified version, rather, we simply changed the terminology that appeared on the screen to make it more understandable to children. For completeness, in this description we will provide the terminology used in the first version of the Chores software in parentheses after the description of the modified version.

The participant interacts with the computer to navigate around a map of a city using the mouse and/or arrow keys. (A sample map screen can be seen in Fig. 1.) The participant has two lists beside the map; a "*you have*" list which displays items the participant has been given or has acquired at one of the locations on the map, and below it a "*you need* " list (*"inventory items"* and *"required item"* were used in the initial version of Chores) which displays items the participant must acquire in order to complete the task. Icons in the form of abstract symbols (e.g., triangles, circles, etc.) represent either items to acquire or items the participant has in her inventory.

Each location on the Chores map has an associated action (i.e., an operator which transforms the problem space) that is performed when the participant visits that location. Actions are specified in a form similar to that of STRIPS operators. There are three components associated with each place/location in Chores: (1) Each location has a precondition which determines whether the participant would be allowed to enter. Specifically, these are items the participant must have in her inventory in order for the action associated with that location to be performed. We used the term "*needs key* " to label preconditions in the user-interface because it suggests the analogy of needing a key in order to enter a building ("*requires* " was used in the initial Chores version). (2) Each location has a specific item which is added to the participant's inventory upon performance of the action. We used the term "*gives* " in the user interface ("*Adds* " was used in the initial Chores version). If an item is on the "you need" list previous to the execution of the action, then it is deleted from that list when that action is performed. (3) Each location has a specific item which is deleted from the participant's inventory upon performance of the action. We used the term "*takes* " in the user interface ("*Deletes* " was used in the initial Chores version). If an item on the delete list is not in the participant's "you have" list at the time the action is performed, then that particular delete specification has no effect. Thus, when a participant "arrives" at a particular location on the Chores map, the action associated with that location is performed; that is, the participant's inventory is checked to determine whether the item specified by the "needs key" is in the inventory. If the inventory contains that item, the item to be deleted is taken away from the participants' inventory (if it is in the inventory), and the item to be added is added to the participant's inventory and removed from the "you need" list. If the initial precondition is not met-that is, the participant does not have the "needs key" item in her inventory-then the other components of the action are ignored.

A separate screen, accessed by pressing an "Item Information" button, lists each location along with the components of the associated action (Fig. 2). The time a participant spends looking at this screen is recorded and is interpreted as planning time. A participant may also backtrack while viewing the map screen by clicking an "Undo Previous" button. The Undo Previous button can be pressed until the first chore the participant completed has been undone. This, and all other actions taken by the user, are recorded and time-stamped for analysis.

The particular configuration of Chores used in this experiment was based on Barrett and Weld's (1993) D^1S^1 experimental domain. Since each operator in D^1S^1 deletes the precondition of the operator that directly precedes it, for each task there is only one correct sequence of actions that will achieve all goals. The Chores D^1S^1 series consists of two training trials, four test trials, and four foil trials. The four test trials consist of 2-, 3-, 4-, and 5-operator problems that adhere to the D^1S^1 pattern. The foils consist of similar problems that do not adhere to the D^1S^1 pattern. These foils helped to assure that the participant did not realize the

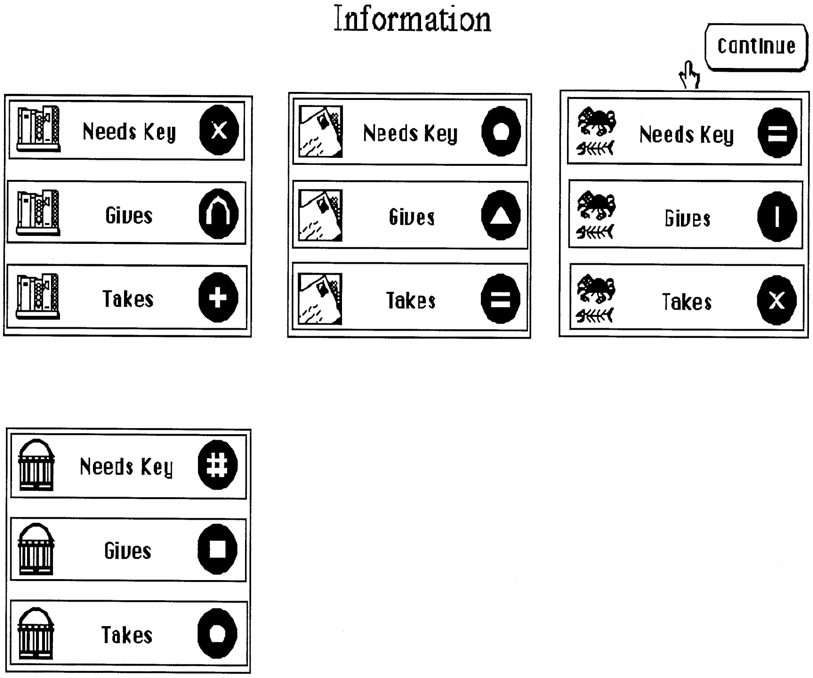

Fig. 2. Sample display from the Chores Item Information Screen.

domain characteristics and utilize specialized procedures for D^1S;[1] because the foils deviated from the D^1S^1 pattern, we can assume that the participants used more general planning strategies to solve the problems.

2.1.3. Procedure

Participants were seated in front of a Macintosh computer with the experimenter seated beside them. The training trials were used to demonstrate the various features of the Chores software. Although the wording of instructions varied slightly between child and adult participants, the following basic ideas were presented:

(1) The goal of this experiment is to obtain a set of items by going to the locations on this map. Each time an item is obtained it is removed from the list of objects to get and added to the inventory.

(2) The places and items on the list are not thematically linked. Thus, going to the "library" will not result in a book being added to the inventory; rather, a triangle will be added.

(3) The small black square designates your position. You can move one square at a time. A particular location is entered by moving the black square into it. (This is demonstrated to the participants.)

(4) The "Information" button gives you a screen that tells you about the locations on the map. Each location needs a key ("needs key" on the information screen) to enter it, and you may not enter unless that object is in the inventory. If a location "gives" an item, then that

item will be added to your inventory when you enter that location. If a location “takes away” an item, if that item is in your inventory when you enter that location, you will lose it. If that item is not in your inventory then nothing will be taken away.

(5) The “Undo Previous” button can be used to undo a previous move. This may be pressed as many time as necessary.

All features were demonstrated by the experimenter, and the participants were asked to experiment with the training trials until they were comfortable with the Chores environment. For the adults, the eight remaining trials were presented according to a Latin square constructed with the four D^1S^1 trials.

After each trial was completed the experimenter saved the protocol and began the next trial for the participant. Participants were encouraged to persist until they completed all of the trials.

2.2. Results

After Barrett and Weld (1993) who found a linear increase in the total time to completion with total-order planners and an exponential increase in total time to completion with partial-order planners, we examined the participants’ total time to completion for a similar pattern of performance. Since aspects of human performance, such as time to execute a plan, are not included in Barrett and Weld’s work, we also analyzed the time spent viewing the item information screen as an additional measure of planning. In addition to examining the quantitative data provided by the Chores experiment, we also analyzed the protocols provided by the computer record of the participants’ performance to detect either total-order or partial-order characteristics in the pattern of participants’ moves. The coding of these protocols will be described in full later.

2.2.1. Total time to completion

Total time was defined as the time in seconds from the first move until the last chore was completed, which included the total time spent planning, revising, and executing the chores. Although the human times would logically be slower, we expected to find similar differences in the patterns of reaction times between participant populations as in run times between computer algorithms. That is, the children and adults with damage to the prefrontal cortex, who we hypothesize to be using total-order plan representations, will display an exponential increase in time spent on this task. In contrast, adults, who we hypothesize to be using partial-order plan representations, will display a linear increase in time spent on this task. As we noted previously, the performance of the older children is difficult to predict.

Our predictions were supported by a Participant Population (adult controls, adults with damage to the prefrontal cortex, younger children and older children) X Number of Chores (2, 3, 4, and 5) analysis of variance which revealed main effects of participant population (F (3, 35) $= 7.97$, $p < .01$), number of chores (F (3, 105) $= 41.33$, $p < .01$), and an interaction between participant population and number of chores, (F (9, 105) $= 3.30$, $p < .01$).[1]

Post hoc analysis of the total time to completion (Bonferonni multiple tests, alpha $=0.05$) revealed that the adults with damage to the prefrontal cortex were significantly slower to finish ($M = 374$ s) than the other populations tested. Specifically, the young children’s mean time to complete all the chores was 238 s, while the adult controls completed all the chores in 180 s, and the older children in 137 s. Note that while the older children were faster than the adult controls, an analysis of the number of constraint violations revealed that the adults committed fewer constraint violations than the older children, suggesting that what the older children gained in speed they lost in accuracy.

Post hoc analyses also revealed that, overall, as the number of chores increased the amount of time necessary to complete the task significantly increased. Specifically, mean total time to completion was 85 s for D^1S^1-2, 155 s for D^1S^1-3, 248 s for D^1S^1-4 and 463 s for D^1S^1-5. All mean times were significantly different from each other.

Crucial to our stated hypotheses, however, is the interaction between the different participant population tested and the number of chores. Recall that we made specific predictions regarding the shape of the function formed by the interaction between participant population and number of chores, with adults, and possibly older children, showing linear increases in reaction time, and young children and adults with frontal damage showing exponential increases in reaction time. To determine the shape of the function formed by each participant population, we submitted their performance to a linear trend analysis. As predicted, there was a significant linear trend in the performance of the adults (F_{lin}(1,45 $=$ 13.74 $p < .01$), and also in the performance of the older children (F_{lin} (1,29) $=$ 37.52, $p <$ .01), suggesting that these populations were using partial-order planning. In contrast, there was both a significant linear and a significant quadratic trend in the total time of both the young children (F_{lin} (1,25) $=$ 50.17, $p < .01$, F_{quad} (1, 25) $=$ 4.42, $p < .05$) and the adults with damage to the prefrontal cortex (F_{lin} (1,43) $=$ 32.50, $p < .01$, F_{quad} (1, 25) $=$ 3.20, $p <$ .05).[2] (See Fig. 3.)

While the quadratic trend found in the data of the younger children and the adults with damage to the prefrontal cortex confirms that their performance was not linear, with this type of analysis it is not possible to say with confidence that their performance was exponential. To determine whether the function formed by their total time to completion was in fact exponential, we took advantage of the fact that when an exponential function is transformed logarithmically it will produce a linear function. Logically, if our data forms an exponential function, after it is logarithmically transformed the function will be linear.

Consequently, we performed a logarithmic transformation on the data of all three populations and a linear trend analysis was again performed. This analysis revealed a significant linear trend in the transformed performance of the young children (F_{lin} (1,25) $=$ 58.07, $p <$ .01) and in the transformed performance of the adults with damage to the prefrontal cortex (F_{lin} (1,43) $=$ 48.77, $p < .01$), confirming that the original data formed an exponential function. Scatterplot diagrams of the residuals versus the predicted values from the data of both populations revealed that the relationship between residuals and predicted values was homoscedastic,[3] suggesting that the assumption of normality in this transformed data were met.

2.2.2. Item information viewing time

Item information viewing time is the total time the participant spent viewing the "Item Information" (action specification) screen. Since this is the screen in which the ordering constraints are viewed (and therefore ordered), we believed this to be a measure of "pure"

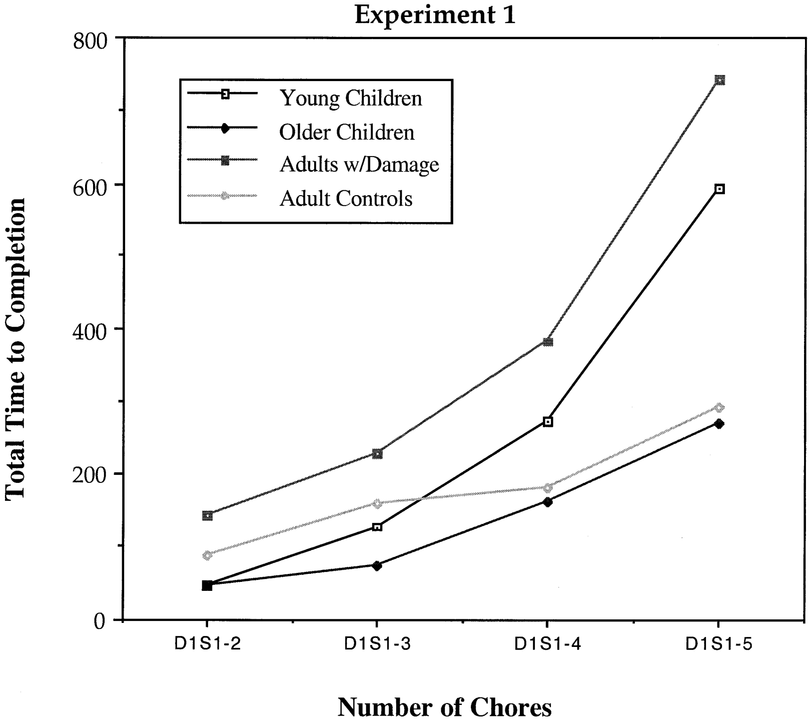

Fig. 3. Total Time to Completion in Experiment 1.

planning time. The data for the item information viewing time revealed a main effect of number of chores, with viewing time increasing with number of chores. This was confirmed by a Participant Population (adult controls, adults with damage to the prefrontal cortex, young children, and old children) X Number of Chores (2, 3, 4, and 5) analysis of variance which revealed main effects of participant population (F (3, 35) = 6.96, $p < .01$) and number of chores (F (3, 105) = 48.82, $p < .01$), as well as an interaction between population and number of chores ($F(9,105) = 2.78$, $p < .05$).

The main effect of chores reflects the increasing difficulty in the chores task as the number of operators increased, increasing from a mean of 26 s spent viewing the Item Information screen for the two-chores task to 60 s for the three-chores task, 109 s for the four-chores task and 214 s for the five-chores task.

As can be seen in Fig. 4, we again found the crucial interaction between participant population and number of chores. There was a significant linear trend in the performance of the adult controls (F_{lin}(1,45 = 14.94, $p < .01$) and both a significant linear and a significant quadratic trend in the time spent viewing the Item Information screen for the young children (F_{lin} (1,25) = 39.61, $p < .01$, F_{quad} (1, 25) = 6.36, $p < .05$), as well as for the adults with damage to the prefrontal cortex (F_{lin} (1,43) = 32.80, $p < .01$, F_{quad} (1, 25) = 4.12, $p < .05$). Unlike the analysis of the total time to completion, the older children displayed both a significant linear and a significant quadratic trend in their performance (F_{lin} (1,25) = 71.98, $p < .01$, F_{quad} (1, 25) = 6.32, $p < .01$).

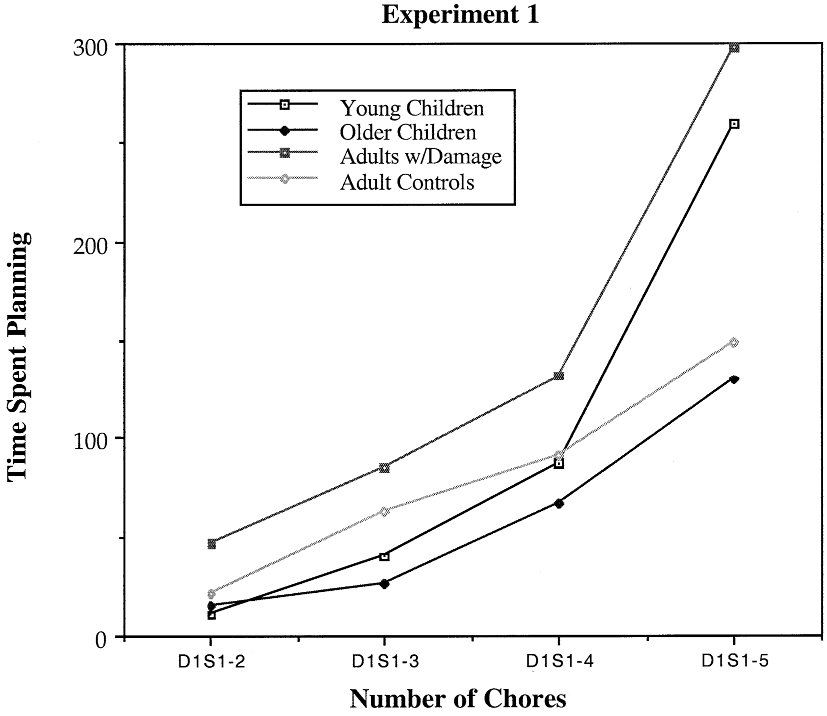

Fig. 4. Time Spent Planning in Experiment 1.

A logarithmic transform was performed on the data of all three populations followed by a linear trend analysis. This analysis revealed a significant linear trend in the transformed performance of the young children (F_{lin} (1,25) = 62.8, $p < .01$), the older children (F_{lin} (1,29) = 97.7, $p < .01$), and in the performance of the adults with damage to the prefrontal cortex (F_{lin} (1,43) = 42.33, $p < .01$), confirming that the original data from these populations formed an exponential function. Scatterplot diagrams of the residuals versus the predicted values from the data from all three populations revealed that the relationship between residuals and predicted values was homoscedastic, suggesting that the assumption of normality in this transformed data has been met.

2.2.3. Protocol analyses

The protocols produced by the Chores software were analyzed for characteristics of either total-order or partial-order planning. To do this we analyzed the participants' use of the "undo" command, which could be used to reverse a previously performed chore. We found that in all of the populations tested the most prevalent use of the undo command was immediately after a constraint violation, suggesting that both partial-order and total-order planners realized that their plan had failed and were attempting to repair it. Recall from our previous characterizations of total-order and partial-order planners that we predict very different patterns of behavior at this point. For the total-order planners we predict that a constraint violation will lead to "undoing" all of the previously performed chores (in effect,

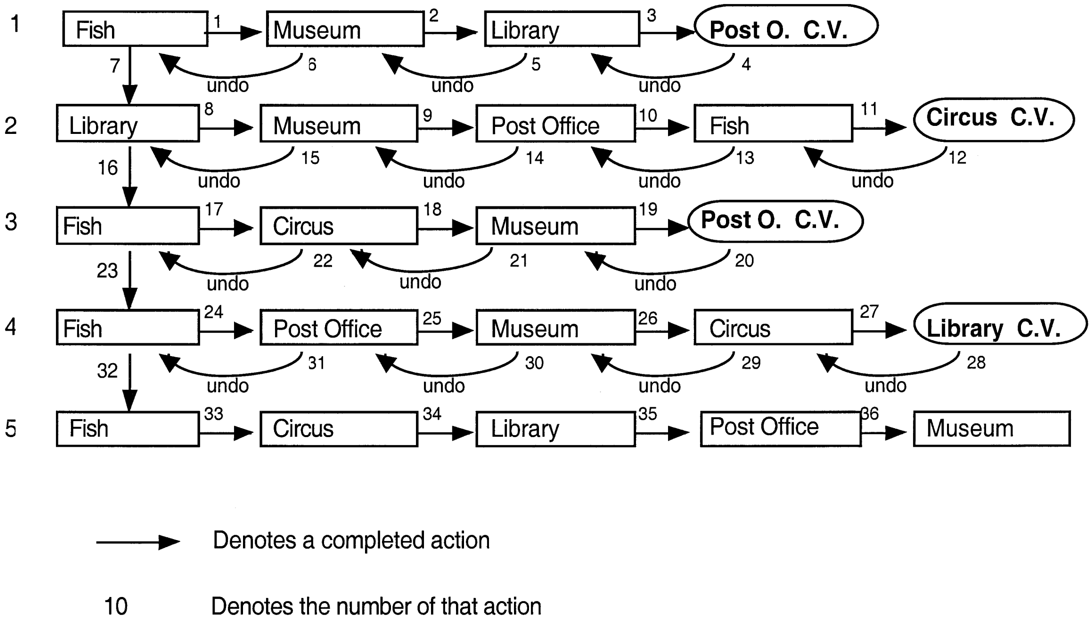

Fig. 5. Example of total-order planning.

starting over from the beginning) and devising another total-order plan. For the partial-order planners we predict that a constraint violation and the need to replan will lead to “undoing’’ the chores relevant to the current partial plan, with the other completed chores remaining intact. The partial-order planner will then devise another partial plan to complete the remaining chores.

Only the protocols from the participants’ performance on the 4 and 5 constraint problems were analyzed. Each protocol was examined for the use of the “undo” command, and the extent of the backtracking performed by the participant when using the “undo” command was noted. These protocols were then examined for evidence of partial-order or total-order planning. A participant was categorized as a total-order planner if she displayed one of the following characteristics in the completion of either D^1S^1-4 or D^1S^1-5: 1) she “undid” all of her completed chores, including the initial chore performed, and then began her new series of chores by repeating the initial chore that had just been deleted, or 2) “undid” all of her completed chores and began a completely new sequence at least three times in the course of completing her chores. The first characteristic, immediate repetition of a deleted initial chore, suggests that the participant had formed a plan representation, discarded it when it failed, and then formed a completely new plan representation. This new plan, however, repeats the initial chores ordering of the discarded plan, suggesting that the participant is unable to leave a partial-plan in place while forming other partial plans–she must instead delete all of her completed chores and form a completely new, total-order, plan representation. This pattern can be seen in Fig. 5, which schematically represents a young child’s total-order planning. In this five chore task the correct order is Fish Market, Circus, Library, Post Office and

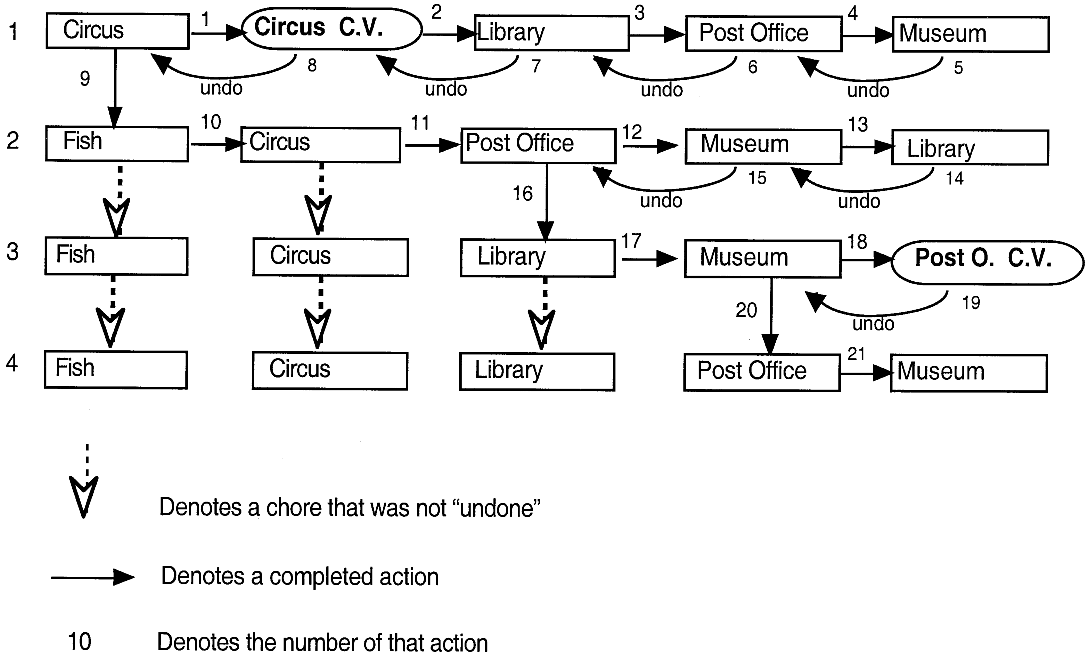

Fig. 6. Example of partial-order planning.

Museum. Note that after her first three moves (Fish Market, Museum and Library) the participant encounters a constraint violation (C.V.) when she tries to enter the Post Office. She then "undoes" her moves back to the beginning and replans. On her third attempt at finishing the chores, this participant begins with two correct moves (Fish Market and Circus), but when she again commits a constraint violation she "undoes" all of her moves—even the correct ones. She then begins her fifth attempt by repeating the moves she had recently "undone."

The second characteristic is designed to ensure that partial -order planners who begin with an incorrect first chore are not mistakenly categorized as total-order planners. The logic of this characteristic is simple; if a participant begins with an erroneous first move, she must completely "undo" all the chores in order to finish the task despite possessing the ability to form partial-order plans. We believe, however, that when a participant consistently forms and then discards a series of total-order plans it is because that participant is unable, or unwilling, to use the more efficient partial-order planning representation.

The categorization of a participant as a partial-order planner was quite straightforward; a participant was considered a partial-order planner if she "undid" only a portion of the chores performed (assumedly "undoing" back to the error in planning) and then continued with a new partial plan. As can be seen in Fig. 6, (an example from an adult partial-order planner), these participants responded to a constraint violation by "undoing" only back to the incorrect move, leaving intact moves that were correct. For example, in his second attempt to solve the chores task, this participant began with two correct moves, the Fish Market and the Circus, but came to the end of his chores and had not moved all the items from the "you need" to the “you have” list. Consequently he “undid” his last three moves, leaving intact the first two correct moves. He then continued planning from that point.

Using these criteria, we categorized those participants who used the “Undo Previous” key during the course of solving the four and five constraint chores problems. This analysis revealed several different patterns of performance in the populations tested. First, the analysis of the adult control participants’ protocols suggests that they consistently used partial-order planning. Specifically, of the three adult controls that used the “Undo Previous” command, all three displayed a pattern characteristic of partial-order planning. Second, the analysis of the older children’s protocols suggests that this population is in a transitional state, with some participants using total-order plan representations and others using partial-order plan representations. Of the six older children who used the “undo” command (and the majority of the children did consistently “undo” several of their moves), the pattern of performance for two participants suggested total-order planning, while the pattern of performance for four participants suggested partial-order planning.

Third, the younger children were consistently total-order planners, as were the majority of the adults with damage to the prefrontal cortex. All six of the younger children who consistently used the “Undo Previous” key were classified as total-order planners, while five of the eight adults with damage to the prefrontal cortex who used the ‘Undo Previous“ key were classified as total-order planners, two as partial-order planners, and one was unclassifiable.

2.3. Discussion

In this experiment we investigated planning abilities among different populations by comparing the performance of children, adult controls and adults with damage to the prefrontal cortex on a planning task in a well-defined domain. Based on the performance of artificial planners in the D^1S^1 domain (Barrett & Weld, 1993), as well as previous research (Grafman, 1989; Hayes-Roth & Hayes-Roth, 1979, Pea & Hawkins, 1987; Spector, Rottermann, Prentice & Juneau, 1994), we hypothesized different patterns of performance across the different participant populations; young children and adults with damage to the prefrontal cortex would use inefficient total-order plan representations, while adult controls, and possibly older children, would use efficient partial-order plan representations. These differences in planning would be reflected in a variety of measures: total time to completion, time spent viewing the Item Information screen, and characteristic patterns of performance in the experimental protocol.

We found that the adult controls exhibited performance suggestive of partial-order planning: linear increases in problem-solving time, linear increases in time spent viewing the item information screen, and experimental protocols supportive of partial-order planning. Children aged 7–8 years and adults with damage to the prefrontal cortex, however, exhibited performance suggestive of total-order planning: exponential increases in problem-solving time, exponential increases in time spent viewing the item information screen, and experimental protocols supportive of total-order planning. The performance of the older children is more difficult to interpret; although their total time to completion suggests that they were using partial-order planning (a linear increase in time to completion as the number of chores increase), their time spent viewing the Item Information screen suggests that they were using total-order planning (an exponential increase in time spent viewing the Item Information screen as the number of chores increased). Further, the analysis of the protocols generated by the Chores software suggests that two thirds of the older children tested displayed partial-order planning, however, one third displayed total-order planning. Thus, the data from the older children suggest that they are in a transitional period–while many children in this age range can perform partial-order planning, many cannot. From a neurophysiological perspective the performance of the older children is not a surprise; it has been hypothesized that the human prefrontal cortex reaches its final maturity between the ages of 12 and 15 years (Goldman-Rakic, 1987; Prather & Gardner, 1992). Thus, early adolescence can be seen as a time of transition between the cognitive functioning of a young child and that of an adult.

We offer two interpretations of the performance of the young children and the adults with damage to the prefrontal cortex. The first interpretation is based on differences in memory capacity between the populations tested, that is, the inefficient performance of children and adults with damage to the prefrontal cortex is due to a common lack of memory capacity. Research in the developmental literature (e.g., Kail, 1991, Pascuale-Leone, 1987) has suggested that young children have less *cognitive capacity.* That is, the capacity of their short-term memory is not comparable to that of adults. If this is the case, these participants' performance on the Chores task, particularly the exponential increase in response time, reflects their inability to hold (relatively) large amounts of information in short-term memory. On this interpretation, it is possible that young children and adults with damage to the prefrontal cortex are capable of using partial-order plan representations but do not possess the memory capacity necessary to manipulate these more sophisticated representations. Instead, they use the less complex total-order plan representations.

A second interpretation is based on a hypothesized *production deficiency* (Flavell, Beach & Chinsky, 1966); the performance of children and adults with damage to the prefrontal cortex is due to a common inability to form and use partial-order plan representations. If this is the case, the exponential increase in response time, as well as the other measures taken, reflect an inability to form partial-order plans. On this interpretation, these populations simply cannot form the appropriate representations for partial-order planning, regardless of the memory constraints inherent in the task. Because of their inability to form partial-order plan representations, they must use inefficient total-order plan representations. Differentiating between these two interpretations is one of the goals of Experiment 2.

3. Experiment 2

Results from the variety of measures used in the previous experiment supported our hypothesis that young children and adults with damage to the prefrontal cortex use total-order plan representations, while older children and adults use partial-order plan representations. These differences in performance could be due to memory limitations in young children and adults with damage to the prefrontal cortex—they simply do not have the memory capacity to retain the information necessary to use partial-order plan representations. Alternatively, the young children and adults with damage to the prefrontal cortex could be exhibiting a production deficiency due to immaturity or damage, they are simply unable to form a partial-order plan representation.

To differentiate between these two interpretations, we designed a second experiment that altered the memory demands of this task. Specifically, we presented participants with the Chores problem set on three different days. The logic of this manipulation is quite simple; by repeating the task several times we have made the Chores domain more familiar to the participants, thereby decreasing the memory demands inherent in the task. If it is memory capacity, and not the inability to form partial-order plan representations, that is hindering the young children then the repetition of the Chores tasks will decrease memory load and enable them to use partial-order plans. If, in contrast, even forming partial-order plan representations is outside of their abilities, their reaction times and other measures will continue to indicate total-order planning.

An additional goal of this experiment is to further explore the role of neurological development in planning ability. Recall that the older children tested in Experiment 1 appeared to be in a transitional period between the use of partial-order and total-order planning. We suggested that one reason for this change in planning representation may be due to the effects of neurological development. In this experiment we are testing a slightly older age group, 11 to 14 year-olds, to determine the age at which partial-order planning becomes the predominant planning style.

We further examined the role of neurological change by testing a population of adolescents who had suffered damage to their prefrontal cortex when they were children. Populations such as this often do not show massive cognitive deficits as adults; the plasticity of the brain allows them to fully develop many of the functions that, in normal populations, usually occur in the areas where they have sustained damaged. However, given the specific nature of the planning tasks we used in this research, it was our thought that any subtle differences between this population and the normal population would be evident in the Chores domain.

In sum, we tested three different populations in this experiment: young children (7- and 8-year-olds), adolescent controls (11- through 14-year-olds), and adolescents who suffered damage to the prefrontal cortex as children (11- through 15-year-olds). Because the adult controls in the previous experiment were already partial-order planners in only one session, we felt it unlikely that they would change strategies across sessions, and they were not included in this experiment.

3.1. Method

3.1.1. Participants

Nine children between the ages of 7 and 8 years (4 males and 5 females), 4 children between the ages of 11 and 14 years (2 males and 2 females), and 9 adolescents between the ages of 11 and 15 years with damage to the prefrontal cortex (4 males and 5 females) were tested in this experiment. (See Table 1.) The nonlesioned controls were recruited from the general population of the Swarthmore, Pennsylvania area. Most participants were from a middle class background.

3.1.2. Materials

The chores software used in Experiment 1 was again used.

3.1.3. Procedure

The participants were tested using the four D^1S^1 trials of the Experiment 1. The trials were presented three times on three separate days, over the period of one week, and were presented in a different random order on each of the three days. Because the young children in the previous experiment often complained of the number of Chores tasks to be performed, we tested the children on all four D^1S^1 tasks, but only two of the foils. No modifications were made to the basic Chores stimuli.

3.2. Results

3.2.1. Total time to completion

As in the previous study, as the number of Chores increased the overall time taken to complete these chores increased (57 s for D^1S^1-2, 97 s for D^1S^1-3, 173 s for D^1S^1-4, and 330 s for D^1S^1-5). Not surprisingly, the total time to completion decreased significantly over the three days of testing, from 248 s on Day 1, to 137 s on Day 2, to 107 s on Day 3. There was a marginal effect of participant population, with the adolescent controls and the adolescents with damage to the prefrontal cortex finishing the Chores task in the same amount of time (149 s for the adolescent controls, 137 s for the adolescents with damage to the prefrontal cortex), and both of these groups finishing faster than the young children (202 s). The most interesting aspect of this data lies in the interaction between the number of times the Chores task had been repeated, the number of chores to be performed, and the participant population (See Fig. 7). Over the three days of testing, the younger children progressed from an exponentially rising total time to completion on Day 1, a somewhat less extreme exponential function on Day 2, and linear performance on Day 3. Note that the results from Day 1 of this experiment provides us with a replication of our findings from Experiment 1; in their first experience with this task, the young children again showed an exponential increase in total time to completion as the number of chores increased. The adolescent controls and the adolescents with damage to the prefrontal cortex displayed linear total times to completion on all three days of testing.

A Participant Population (young children, adolescent controls, and adolescents with damage to the prefrontal cortex) X Session (Day 1, Day 2, and Day 3) X Number of Chores (2, 3, 4, and 5) analysis of variance revealed a marginal main effect of participant population (F (2,18) = 2.98, $p < .1$), main effects of session (F (2, 36) = 11.65, $p < .01$), and number of chores (F (3, 54) = 32.45, $p < .01$). There were also significant interactions between participant population and number of chores (F (6,54) = 2.67, $p < .05$), session and number of chores (F (6,108) = 4.44, $p < .01$), and a three-way interaction between participant population, session, and number of chores (F (12,108) = 1.92, $p < .05$).

To determine the shape of the function formed by each participant population on each day of testing, we submitted their performance to a linear trend analysis. We found both a significant linear and a significant quadratic trend in the total time of the young

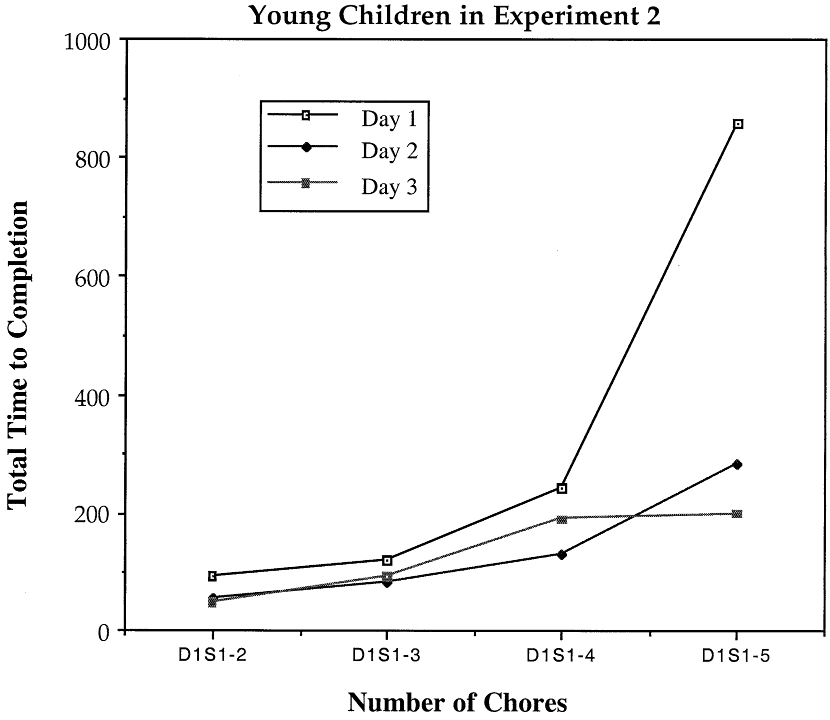

Fig. 7. Total Time to Completion in Experiment 2.

children on Day 1 (*F*lin (1,33) = 25.88, $p < .01$, *F*quad (1, 33) = 7.70, $p < .01$), as well as on Day 2 (*F*lin (1,33) = 46.78, $p < .01$, *F*quad (1, 33) = 7.13, $p < .01$), and a significant linear trend on Day 3 (*F*lin(1,45 = 4.87 $p < .05$). This data can be seen in Fig. 7.

In order to confirm that the quadratic trends found in the data were in fact exponential functions, a logarithmic transform was performed on the data and linear trend analyses were again performed. These analyses revealed a significant linear trend in the transformed performance of the young children on Day 1 (*F*lin (1,33) = 75.16, $p < .01$) and on Day 2 (*F*lin (1,33) = 101.69, $p < .01$), thus confirming that the original data formed exponential functions. Scatterplot diagrams of the residuals versus the predicted values from the data from Day 1 revealed that the relationship between residuals and predicted values was homoscedastic suggesting that the assumption of normality in this transformed data has been met, however, the data from Day 2 was slightly heteroscedastic.[4]

When examining the performance of the adolescent controls we did not find a significant linear trend in their total time to completion on Day 1 (F_{lin} (1,13) = 2.90, $p >$ .05), but the trend did appear on Day 2 (F_{lin} (1,13) = 14.25, $p < .01$) and on Day 3 (F_{lin}(1,13 = 5.08 $p < .05$). We also found linear trends in the performance of the adolescents with damage to the prefrontal cortex on all three days of testing (F_{lin} (1,33) = 24.21, $p < .01$ for Day 1, F_{lin} (1,33) = 29.04, $p < .01$, for Day 2, and F_{lin} (1,33) = 31.57, $p < .01$ for Day 3).

3.2.2. Item information viewing time

These analyses revealed a pattern of responding similar to that found in the total time to completion. Collapsed across all three populations, as the number of Chores increased, the mean time spent viewing the Item Information screen increased (13 s for D^1S^1-2, 29 s for D^1S^1-3, 60 s for D^1S^1-4, and 126 s for D^1S^1-5). There was also an effect of practice and familiarity on the participants' performance; the mean time spent viewing the Item Information screen across all three populations decreased significantly over the three days of testing, from 87 s on Day 1, to 45 s on Day 2, to 39 s on Day 3. There was no effect of participant population; all three participant populations spent approximately the same amount of time viewing the Item Information screen (71 s for the adolescent controls, 42 s for the adolescents with damage to the prefrontal cortex, 66 s for the young children). Again there was an interaction between the number of times the Chores task had been repeated, the number of chores to be performed, and the participant population. Over the three days of testing, the younger children progressed from an exponentially rising time spent viewing the Item Information screen on Day 1, a somewhat less extreme exponential function on Day 2, and linear performance on Day 3. The adolescent controls and the adolescents with damage to the prefrontal cortex displayed linear times to completion on all three days of testing.

A Participant Population (young children, older children, and adolescents with damage to the prefrontal cortex) X Session (Day 1, Day 2, and Day 3) X Number of Chores (2, 3, 4, and 5) analysis of variance revealed a main effect of session (F (2, 36) = 18.18, $p < .01$) and number of chores (F (3, 54) = 27.20, $p < .01$). There were also significant interactions between session and number of chores (F (6,108) = 3.47, $p < .01$) and a marginal three-way interaction between participant population, session, and number of chores (F (12,108) = 1.69, $p < .10$).

To determine the shape of the function formed by each participant population on each day of testing, we submitted their performance to a linear trend analysis. We found a significant linear trend in the planning time of the young children on Day 1 (F_{lin} (1,33) = 14.57, $p < .01$), a significant linear trend and a significant quadratic trend on Day 2 (F_{lin} (1,33) = 78.57, $p < .01$, F_{quad} (1, 33) = 9.03, $p < .01$), and a significant linear trend on Day 3 (F_{lin} (1,45 = 7.00 $p < .05$).

In order to confirm that the quadratic trend found in the data were in fact an exponential function, a logarithmic transform was performed on the data and the linear trend analysis was again performed. This analysis revealed a significant linear trend in the transformed performance of the young children on Day 2 (Flin (1,33) = 7.58 $p < .01$), thus confirming that the original data formed an exponential function.

We found a significant linear trend in the performance of the adolescents with damage to the prefrontal cortex on all three days of testing (F_{lin} (1,33) = 18.95, $p < .01$ for Day 1, F_{lin} (1,33) = 41.92, $p < .01$, for Day 2, and F_{lin} (1,33) = 22.40, $p < .01$ for Day 3), and a significant linear trend in the performance of the adolescent controls on the first two days of testing (F_{lin} (1,13) = 6.33, $p < .01$ for Day 1, F_{lin} (1,13) = 7.65, $p < .01$, for Day 2).

3.2.3. Protocol analyses

An analysis of the participants' use of the "Undo Previous" key was again performed. Based on the data from total time to completion and the item information viewing time, we

Table 2
Results from the protocol analyses performed in experiment 2

Young children	Day of testing		
	Day 1	Day 2	Day 3
Spe	Total	Partial	Partial
Eli	Total	N/A	N/A
Jus	Total	N/A	N/A
Bea	Partial	N/A	N/A
Sam	Partial	N/A	N/A
Mat	N/A	Partial	N/A
Rac	N/A	N/A	Partial
Adolescents with damage			
Mau	Total	Total	Total
Sco	Total	Total	N/A
Owe	Total	N/A	N/A
Cer	Total	N/A	N/A
KAD	Partial	Partial	Partial

hypothesized that the young children would show protocols suggestive of total-order planning on Days 1 and 2 and protocols suggestive of partial-order planning on Day 3. Also, again based on total time to completion and time spend viewing the Item Information screen, we predicted that the adolescent controls and adolescents with damage to the prefrontal cortex would show protocols suggestive of partial-order planning on all three days of testing.

The data from the young children revealed that on Day 1 of testing, three out of the five participants who used the “Undo Previous” key produced protocols suggestive of total-order planning, while two produced protocols suggestive of partial-order planning. (The data from this analysis can be seen in Table 2.) It is interesting to note that on Days 2 and 3, several of the children displayed patterns suggestive of partial-order planning. Most notable is the participant Spe, who displayed total-order planning on Day 1 and partial-order planning on Days 2 and 3. In fact, none of the children displayed total-order planning on Days 2 and 3, while three did display partial-order planning. The data from the older children did not reveal any use of the “undo” key and, therefore, could not be analyzed in this fashion.

The data from the adolescents with damage to the prefrontal cortex revealed a somewhat surprising pattern of results. Recall that the time to completion, as well as time spent viewing the Item Information screen, both formed linear functions suggestive of partial-order planning. The protocol analysis of this population revealed, however, that of the seven participants using the “Undo Previous” key, only one displayed a pattern characteristic of partial-order planning, while four displayed patterns characteristic of total order planning. Further, for two of those participants, the use of total-order plan representations continued into Day 2, and for one, Mau, it continued into Day 3.

4. General discussion

Motivated by empirical results from artificial intelligence, we performed two experiments comparing planning ability in several different populations. In these experiments, adults and older children exhibited performance on planning tasks of varying complexity which matched that of artificial partial-order planners. This pattern of performance did not vary with multiple presentations of the planning task. Young children (7–8 years of age) and adults with damage to the prefrontal cortex, however, exhibited performance matching that of artificial total-order planners. This pattern or performance did vary, however, with multiple presentations of the planning task; specifically, in the first two sessions the young children displayed a pattern characteristic of total-order planning, while in the third session they displayed a pattern characteristic of partial-order planning. Finally, adolescents who had sustained damage to the prefrontal cortex as children displayed two different patterns of performance; when measures of reaction time were analyzed they revealed a pattern of performance suggestive of partial-order plan representations. However, analyses of the adolescents' protocols revealed a pattern of performance suggestive of total-order plan representations.

4.1. Implications for psychology

Our experiments reveal new insight into the nature of planning. Much of the planning literature has been based on Hayes-Roth and Hayes-Roth's (1979) model of planning (De Lisi, 1987; Kreitler & Kreitler, 1987; Pea & Hawkins, 1987). Our data on partial-order planners supports and elaborates upon this theory in several respects. First, partial-order planners in the D^1S^1 task plan opportunistically. Partial-order planning involves organizing small subsets of goals and reevaluating the problem space (low level of abstraction), and then incorporating these subsequences into a general plan (high level of abstraction). Second, partial-order planners, like the Hayes-Roth planners, utilize event-driven processes in their mental simulation of the planning problem. That is, the planner steps through the abstract sequences of actions (in our case, chores), updating the current state of the domain at each step. Note that the present studies do not address time-driven processes in participants' mental simulation due to task characteristics. Future tests might incorporate this factor by limiting the time a participant has to complete the chores. Third, the concept of partial-order planning fits in quite well with the Hayes-Roths' opportunistic planning model. In their model, Hayes-Roth and Hayes-Roth describe the work of "specialists" during planning; their description also accurately describes the cognitive processes used by partial-order planners when constructing a subsequence in a given plan. In addition, Hayes-Roth and Hayes-Roth describe the use of blackboard data structures that provide a reasonable model for the storage and eventual manipulation of the partial orders.

But what of total-order planners? Our experiment also reveals and makes more explicit the nature of the development of planning skills. We suggest that children undergo a qualitative change in planning skills during early adolescence. Unlike other developmental theorists (De Lisi, 1987; Pea & Hawkins, 1987), we suggest the development of planning skills involves more than the assimilation of metaplanning knowledge. For example, Pea and Hawkins (1987) stress the importance of flexibility in planning strategies. We suggest that this flexibility is manifest in the type of planning strategy used. Partial-order planning, since it delays sequencing until after initial orderings are determined, exhibits great flexibility. It is not enough for children to be aware of the need to be flexible in their ordering decisions, they must also incorporate this principle into an adequate planning skill, such as partial-order planning, in order to utilize it. To be aware of the need to delay ordering decisions is not the same as being able to do it effectively. For our younger participants, planning development would consist of acquiring a new planning skill altogether (i.e., constructing and manipulating partial orders) in addition to gaining knowledge about the nature of planning. The other developmental factors which influence this acquisition are not known, however, we can speculate that development of the prefrontal lobe of the brain plays an important role (Spector, Rattermann & Prentice, 1994; Spector, Rattermann, Prentice, & Juneau, 1994). The development of other cognitive skills crucial to partial-order planning might also influence planning. Abstract reasoning capabilities are among the most likely of these skills to be correlated with planning development.

4.1.1. The effects of repetition

We have suggested that planning development consists of acquiring a new planning skill, specifically that of partial-order plan representations, as well as the knowledge of when to use it. Further, we have suggested that a developmental factor that may play a role in the development of planning is neurological maturation. However, the results of our own Experiment 2 appear to refute this hypothesis: over the course of three sessions, young children developed the ability to use partial-order plan representations, without the benefit of increased neurological maturation. This pattern suggests that learning does account for our pattern of results, particularly when considering the performance of participant Spe, whose protocols showed a shift from total-order planning on Day 1 to partial-order planning on Days 2 and 3. This pattern suggests that learning alone could account for our results, and in fact, other work in the development of planning has shown that the acquisition of *general event representations,* or spatially and temporally organized schematic representations constructed from experience in real-world events (Nelson & Gruendel, 1981, 1986), can significantly improve children's performance in a planning task (Hudson, Sosa & Shapiro, 1997). Thus it is possible that experience and learning could have led to linear patterns of responses that we noted in Sessions 2 and 3, and, in fact, we did note that the children exhibited the learning of highly efficient task specific planning. For example, many of the young children tested used their hands to draw lines or to designate connections between the icons in the Item Information screen, often tracing the path of the chores on the screen or blocking out with their hands the chores already performed. These spatial strategies were all based on lining up the "you need" icon with the "takes away" icon to determine the ordering of each chore. Another child was observed to be chanting the order in which the chores were to be performed, dropping each chore off of the chant as it was completed. This participant was in fact Spe, the participant whose protocol suggested partial-order planning on Days 2 and 3.

These behavioral patterns suggest that the children were using strategies for the Chores task that were not partial-order planning or total-order planning; rather, they may have been strategies learned in other domains that worked within the demands of the Chores task. One possible strategy the children may have been using is *progressive deepening search* (Newell & Simon, 1972).[5] In progressive deepening search a participant implements a series of linear searches without branching, going as deeply in the search tree as necessary to solve the problem. A simple loop function allows him to select only one move at each position in the search tree, and after evaluating its effectiveness, move ahead. As Newell and Simon note, one benefit of this search strategy is to lower *cognitive strain* (Bruner, Goodnow & Austin, 1956). The participant does not need to keep track of complicated past search patterns; rather he only needs to evaluate his current position in light of his original position. Thus, in the more complicated 4 and 5 Chore problems when the child reached an impasse due to constraint violations, he would simply "undo" the moves he could remember from his search, and if he could not remember the relevant moves he would simply start over. Although this kind of simple search is not the most expedient strategy for the Chores tasks, it is an adaptive strategy in that it does allow the child to solve the problem with a minimum of cognitive strain.

Children's ability to adapt their planning styles to the characteristics of the planning domain has also been noted by Gardner and Rogoff (1990) who found that children as young as 4 years old adapted their styles according to instruction from the experimenter. Specifically, when speed was emphasized children made more mistakes but completed the planning problem (in this experiment a maze) in less time. However, when accuracy was emphasized, the children made fewer mistakes while taking longer to complete the task. In addition to providing an example of task effects on planning, the work of Gardner and Rogoff also provides an example of the speed-accuracy tradeoff we believe took place between the adults and the older children in Experiment 1. While neither speed nor accuracy was emphasized to any of the participants per se, it appears as though the adults focused on accuracy in this task, while the 11–12 year-olds focused on speed. This conjecture is supported by Ellis and Siegler (1997), who noted that mature reasoners will often differ from younger, less successful, participants in the amount of time spent planning and the overall success of the task. Thus, in addition to the acquisition of new planning skills, such as partial-order plan representations, children may also be acquiring new task specific strategies to aid them in their planning as well as using new knowledge such as general event representations.

4.2. Implications for neuroscience

In the cognitive neuroscience literature, tests from the Porteus Mazes to the Tower of Hanoi task have been described as requiring planning as well as the execution of a plan. Patients with prefrontal cortex lesions appear especially susceptible to failing such tasks. In order to complete this kind of task, participants are required to "look ahead" several levels deep and solve the problem in their heads before physically attempting to execute the task. If they are impaired on such tasks, the explanation is that they were incapable of searching through the moves in their heads, and that, therefore, they must have a "planning" or "look ahead" deficit. Goel and Grafman (1993, 1995) have articulated an alternative explanation that implies that participants who fail such tasks are, at least sometimes, unable to interrupt a planned sequence of actions in order to make a counterintuitive move. This failure is not so different from the strategies seen in our younger children and patients with prefrontal cortex lesions who could not adapt a partial-order plan and instead opted for the total-order plan regardless of whether it was the most effective way to complete the chores they were assigned. These participants rigid use of total-order planning is compatible with the findings of Goldman-Rakic (1987a; 1987b) who proposed that associative memory is intact in patients and nonhuman primates with damage to the prefrontal cortex, while more flexible, “on-line” processing is impaired. Our prefrontally –damaged and immature participants display of total-order planning could be seen as an example of the routinized responses stored in associative memory, and intact in these populations. Further support for our findings comes from the work of Bechara, Damasio, Tranel and Damasio (1997) who found that when presented with a complex decision-making task, patients with prefrontal damage perseverated in using disadvantageous strategies even after knowing the correct strategy.

While Goel and Grafman were compelled to be cautious about whether the Tower of Hanoi task was even a good instrument for examining planning, there can be no doubt that the methods we used in our studies are well within the confines of the traditional AI planning literature. Our findings substantiate that patients with prefrontal cortex lesions do, in fact, have difficulty in managing plans efficiently even when controlling for memory ability. Grafman (1994, 1995) has argued that the prefrontal cortex stores representations in the form of structured event complexes (SECs) that capture unique aspects of a sequence of activities (such as thematic and grammatical structures) and are necessary to guide the construction and execution of plans. He has claimed that the number of events stored within an SEC can expand until the child reaches the age of 15, in conjunction with the maturation rate of the prefrontal cortex. Thus, Grafman claims that some redundancy of plan representation would exist in human prefrontal cortex and that humans would have access to both total and partial plans. Within that framework, one hypothesis is that an immature prefrontal cortex or damage to the prefrontal cortex affects the ability to shift between levels of a plan (i.e., between a total-order and partial-order plan in either direction) rather than denying people accessibility to a plan.

The performance of the adolescents with damage to the prefrontal cortex has implications for the plasticity of the human brain. These participants were able to perform this difficult planning task as quickly as control participants, thus leading to an initial conclusion that they were using efficient total-order plan representations. Their protocols, however, indicated that the majority of these participants were in fact forming total-order plan representation. One conclusion to be made from these two patterns of performance is that the adolescents have not been able to use partial-order plan representations and instead have developed strategies that have enabled them to increase the speed with which they use their total-order plan representations. This conjecture is related to our hypothesis that the younger children in Experiment 2 are also showing a pattern of performance suggesting partial-order planning, while in fact using total-order plan representations. Regardless of whether their performance is due to changes in plan representation or the development of new strategies, both populations have learned to use effective methods when faced with a task calling for partial-order planning.

4.3. Implications for AI

The efficiency of the partial-order construct is supported by the results of this study. The AI literature now has a nonmachine test of partial-order versus total-order planning to support time/efficiency claims. AI researchers hoping to model human cognitive processes accurately also receive support in the use of partial-order planning algorithms. In addition, further studies of human planning skills may lead to better computer planning programs.

Research investigating the performance of adult planners has shown that the most effective planning is often associated with the "least commitment" strategy associated with partial-order planning (Stefik, 1981). This kind of planning is in contrast to the process of anticipatory planning (Scholnick & Friedman, 1987), in which the planner sets up an ordered set of procedures which are often ordered serially and constrained by the planner's knowledge. Scholnick and Friedman note that proficient anticipatory planners "think out the entire plan before acting." According to Scholnick and Friedman, anticipatory planning is most appropriate when the goal is well-defined and familiar, while opportunistic planning is appropriate for ill-defined tasks or novice planners.

4.4. An integrated model of planning development

The information-processing view would state that the development of problem-solving abilities depends upon both increasing capacity of basic cognitive facets (e.g., memory, encoding, knowledge base) and the acquisition of more appropriate strategies. We believe that several cognitive elements of planning ability serve as "limiting factors" on the development of planning ability. While an appropriate knowledge base Hudson & Fivush, 1991 and metacognitive skills (Kreitler & Kreitler, 1987; Pea, 1982; Pea & Hawkins, 1987) are necessary for planning, we propose that in our task the choice/availability of a strategy is crucial.

As designed, partial-order planning is a more efficient choice than total-order planning for the Chores task. If, whether because of lack of experience or because of lack of maturation, this strategy is not available to the child, performance on this task will be determined by other factors inherent in the planning task or inherent in the participant. The degree to which these factors influence planning performance also depends upon the planning problem. For example, in the D^1S^1 problem, a rich knowledge base was not necessary, since all problem characteristics were explained to the participant. In contrast, participants in Hayes-Roth and Hayes-Roth's (1979) experiment required a very detailed knowledge of various constraints (e.g., the time a movie would take, time involved in going to the pet store, etc.).

A second factor that may play a role in the obtained results is memory and memory capacity. Developmental researchers have proposed that limitations in memory play a significant role in children's problem-solving and planning abilities (Halford, 1993, Kail, 1991, Ellis & Siegler, 1997). Our experiment demonstrated that planning a task took more time as complexity (and therefore memory demands) increased. Since some strategies (such as partial-order planning) are less demanding of memory than others (such as total-order planning), the type of strategy a participant utilizes will influence how much memory is necessary in order to plan effectively.

We hypothesize that the development of planning ability includes a number of factors including qualitative changes in memory capacity, representational abilities, knowledge base, metacognitive knowledge, and strategy efficiency. Research indicates that qualitative changes in strategy efficiency may be acquired through interaction with adults or peer mentors (Radziszewska & Rogoff, 1988). Future research might investigate the influence of planning instruction on children who exhibit total-order planning strategies.

A computer deals with few problems in memory, representational abilities, and knowledge base in a well-defined problem domain. It follows then that the most significant constraints an artificial planning system faces are metacognitive and strategic. Researchers have demonstrated the value of these elements in artificial planners (Barrett & Weld, 1993; Stefik, 1981). Thus, we propose that artificial planners can best model human performance in problem domains in which all planning factors except strategy and metacognition are trivial. We believe our D^1S^1 Chores configuration to be such a domain and the performance of our participants to be a strong indication of partial and total-order planning strategies in humans.

Notes

1. Each participant population was tested using a set of random orders generated by a different Latin Square design, consequently there were 12 different random orders used. Because these orders varied between the populations tested, order was not included as a variable in the statistical analyses.
2. The linear trend analysis was performed on the data from seven, rather than eight, young children. One of the children's reaction time for D^1S^1-5 was more than two standard deviations away from the mean performance of the group, consequently her data were dropped from this particular analysis.
3. The assumption of homoscedasticity is that the variability in scores for one continuous variable is roughly the same at all values of another continuous variable (Tabachnick & Fidell, 1996)
4. As Tabachnick and Fidell (1996) note, however, heteroscedasticity is not "fatal to an analysis." They state that while the analysis is weakened, it is not invalidated.
5. We would like to thank Kurt VanLehn for his helpful discussion of progressive deepening search and its role in our research.

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