Supervisory Control in a Dynamic and Uncertain Environment: A Process Model of Skilled Human–Environment Interaction

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Abstract—An understanding of how both psychological and environmental factors mutually constrain skilled behavior is required to effectively support human activity. As a step toward meeting this need, a process model of skilled human interaction with a dynamic and uncertain environment is presented. The model was able to mimic human behavior in a laboratory task requiring one- and two-person crews to direct the activities of a fleet of agents to locate and process valued objects in a simulated world. Reflective of the need to explicitly consider both environmental and cognitive influences on behavior, the process model is a pair of highly interactive components that together mimic the behavior of the human–environment system. One component is a representation of the external environment as a dynamically changing set of opportunities for action. This environmental component is based on the ecological viewpoint that relations indicating the match between the human’s capacity for action, and actions made available by the environmental structure, should serve as primitives in the description of the environment for the skilled performer. The second component is a dynamic representation of skilled human decisionmaking and planning behavior within the environment so described. Modeling both human and environment in an integrated fashion allowed for a description of behavior as being mutually influenced by the external environmental structure and an internal priority structure over available actions. Sensitivity to environmental structure ensured that action selection opportunistically exploited the dynamic possibilities for action afforded by the external situation, whereas the priority structure ensured that action selection was also consistent with task goals. The process model is an expression of a general theory of skilled interaction assuming that perception and action mechanisms sensitive to environmental constraints are responsible for generating much of behavior, and where the need for additional cognitive processing of internal representations (e.g., problem-space search, multiple option comparison) may result from environmental designs that do not adequately support the perceptual guidance of activity.

I. INTRODUCTION

When designing many system interfaces, the central issue is not so much how to facilitate human–computer interaction, but rather how to use the computer as an intermediary to facilitate human–environment interaction. The quality of an interface in complex technological systems such as aircraft, manufacturing, and process control is measured in terms of its ability to enhance human interaction with an environment behind the interface, and therefore, questions of display and control design must be addressed within this broader perspective. Although effective human–computer interaction is surely a necessary attribute of a well-designed system, it is far from sufficient since a design must ensure that locally effective activity (at the interface) is also globally effective in terms of overall human–machine system performance. This requirement places strong constraints on models and methods capable of aiding the design of human–machine system interfaces. Most importantly, interface design must be constrained by knowledge of both the cognitive abilities of the human operator and the task-relevant properties of the environment. Psychological models useful for system design and evaluation, therefore, must provide a capability to explicitly represent both the human and the environment, as well as their dynamic interaction. Modeling and design techniques meeting this requirement will provide a basis for ensuring not only fluent and effective human–computer interaction at the interface, but also and most importantly that behavior at the interface is meaningfully related to environmental demands and opportunities. This, after all, is the primary role of the human operator in the system and the true measure of successful human–machine system design.

The purpose of this paper is to present a theory of interface-mediated human interaction with a dynamic, uncertain environment. It is hoped that the theory may prove useful in guiding the design of interfaces to promote effective human activity, and in stimulating greater interest in the problems of constructing integrated models capable of representing the human, the environment, and their dynamic interaction. The theory is applied to describing human–environment interaction in a multivehicle supervisory control task. In this context, a model is presented that explicitly represents the psychological processes of the human operator, the external task environment, and the dynamic interaction between the human and environment during the course of skilled activity. This model was used to successfully mimic the behavior of human subjects...
in the supervisory control task and provided an explanation of how subjects may have used both graphical and alphanumerical displays and sets of both discrete and continuous controls available at the interface to achieve successful performance in this challenging task.

Taking the human–environment system to be the unit of analysis and modeling was fruitful for understanding the psychological demands and possible psychological mechanisms involved in this complex task. One key to achieving a relatively simple account of behavior in this research was the selection of an action-oriented descriptive language for environmental representation. The action-oriented environmental representation allowed much of the dynamic structure in behavior to be readily attributable to the dynamic structure of the environment. Specifically, the present task environment was described as a set of quantitative, dynamic affordance distributions. This form of environmental representation, which was motivated by Gibson’s (e.g., [14], [15]) approach to understanding the role of perception in guiding fluent human–environment interaction, is based on the assumption that relations indicating the match between the human’s action capabilities and the environmental structure should serve as primitives in the description of the environment for the skilled performer.

In the present theory, then, the environment is described as a dynamically varying set of action opportunities competing for the human’s limited resources for cognition and action. Describing the laboratory task environment in this way helped to isolate and measure the environmental contribution in constraining behavior, thereby better isolating the structure in observed behavior not readily attributable to the perceived environment and therefore in need of further cognitive explanation. Any form of human–environment interaction can be described as being mutually influenced by both cognitive and environmental constraints; unless the environmental contribution to behavioral complexity is partialled out, the role of cognitive processes involved in action selection is left unspecified. In the process of modeling, the decomposition of behavioral complexity into its internal and external sources of constraint is an important task. If it is left undone there may be a tendency to postulate complex internal mechanisms to explain structure in behavior that is merely a reflection of environmental structure [50]. The present theory is offered as a candidate approach to this problem in the context of skilled interaction with a dynamic uncertain environment.

The proposed affordance-based environmental representation is neutral with respect to the psychological processes by which these affordances could be detected to guide activity. Here, though, it is suggested that the content and form of displayed information can be examined to determine what information is available to specify the affordances, or action opportunities, at each point in time. In some cases in the present modeling, it was found that the displayed information capable of specifying action opportunities was present in a manner consistent with human perceptual abilities so that actions could be identified and possibly even selected in an efficient perceptual manner. In other cases, the content and form of the displayed information was such that it appeared that cognitive information integration over multiple sources was necessary for the identification and selection of actions. The description of the model details how the environmental representation was created through affordance quantification and how mechanisms representing action evaluation, selection, and implementation were constructed to provide a comprehensive process model of skilled human–environment interaction in this task.

The paper is organized as follows: First, the laboratory task and the experimental results upon which the modeling is based are discussed Section II. A more complete description of the laboratory task and experiments comparing one- and two-person crew performance appears in a companion paper [22]. The theoretical framework for skilled human–environment interaction is presented in Section III, along with a discussion of its theoretical and empirical foundations. The process model of behavior in the laboratory task is presented in two parts. Section IV describes the environmental component of the process model. In that section, the method by which the affordance-based environmental representations were constructed is discussed. Section V describes the cognitive component of the process model. In that section, the mechanisms for action evaluation, planning by look-ahead, and conflict resolution are described. Section VI describes how the process model was parameterized to mimic the behavior of three human crews differing in both crew size and experience level and the tests for empirical adequacy that were conducted. Finally, Section VII discusses implications of this research for psychological modeling and system design.

II. TASK, EXPERIMENTS, AND CREW BEHAVIOR

A. Psychological Research in Supervisory Control

Supervisory control [47] represents an increasingly relevant and challenging domain for the study of skilled behavior in human–machine systems as it appears to make many demands upon the human operator in addition to the psychomotor demands considered in studies of skilled manual control performance. In supervisory control, a person or team interacts with a target system through various intermediary automated or semi-automated systems. For a variety of reasons, supervisory control behavior has most often been studied within the domains of process control [41], [58], manufacturing [10], teleoperation [49], and other complex technological settings, although supervisory control behavior of lesser complexity is ubiquitous in modern life. Any occasion in which a person’s interaction with a target system is performed through a mediating agent will require the person to behave in a supervisory rather than a direct mode of control. Cooking dinner at home while managing the operation of modern kitchen appliances and engaging and monitoring cruise control in an automobile are situations that meet the definition of mediated supervisory control behavior. However, design problems in these task environments have less severe consequences and have therefore drawn relatively little attention (but see [34]).
At a very gross level, psychologically oriented research on supervisory control behavior in complex dynamic systems has been concerned with two general classes of psychological issues. The first focuses on the mechanisms of rare event problem solving involved in fault diagnosis and the nature of human error, motivated to a large extent by design problems in process control environments where the potential consequences of failures and errors can be costly and catastrophic. The high level of automation and the relatively long time constants characteristic of many process control systems has created a situation where the human operator is out of the primary control loop for long periods of time. In such systems, the operator’s most important responsibility is system configuration and reconfiguration in casualty situations. For a collection of papers with this emphasis, see [42], and for an integrative approach, see [43]. In general, this research has a cognitively-intensive orientation as it is concerned primarily with the operator’s possible knowledge structures and internal representations of the controlled system, along with the mechanisms underlying problem solving behavior and the production of human error.

A second general focus of psychological research in supervisory control concerns the mechanisms of skilled performance in complex multitask environments motivated in large part by the problems involved in the design of vehicular control systems. These systems also may have a high level of automation and potential for catastrophic error, but in this class of systems, the time constants and the nature of the task environment are such that the human is an essential component of the primary control loop. The operator serves in a supervisory control capacity, but the frequency of task demands is such that maintaining even steady-state system behavior requires a considerable amount of control activity. Here, many of the major constraints on system performance concern the operator’s ability to effectively determine and implement activity coordinating the many degrees of freedom for system control and in meeting the demands of multiple tasks under considerable time pressure. For a collection of papers with this emphasis see [11], and for integrative approaches, see the discussion of human performance models in [3]. In general, this research has a performance orientation as it is concerned with the mechanisms of skilled behavior, multitask coordination, and mental workload.

This decomposition is admittedly very rough, and it is probably reflective more of distinctions between actual research programs in each of the two general areas rather than of any clear distinction between classes of supervisory control task environments. The majority of supervisory control systems probably raise a mixture of issues related both to problem solving behavior and skilled performance. The laboratory task used in this research required both manual and supervisory control activities in a dynamic and uncertain environment. Modeling behavior required consideration of a wide range of psychological issues, pertaining both to the cognitive processes supporting planning and decision-making, and to the perceptual and action mechanisms underlying skilled performance. The following section gives a brief overview of the task and the experiments that were performed. For more detail on the task and experiments, see the companion article [22].

B. Task and Experiments

The empirical portion of this research is based on a laboratory simulation of a combined supervisory and manual control task in a dynamic uncertain environment. The work station simulated the cockpit of a “scout” craft that could be controlled manually (via joysticks) or by entering waypoints and engaging an autopilot. Crews also had supervisory control over four semi-autonomous craft that could be used to assist the scout in performing the task. The interface could be configured for either one or two-person crews.

Two graphical displays were used. The color map display presented a top-down view of a 100-mi² world indicating irregularly shaped forested regions and the locations of each craft under crew control and was updated approximately once per second. The pilot’s display was a dynamic forward looking view outside the cockpit showing any trees and craft immediately in front of the scout. The pilot’s display also contained a status area in which state and resource information for the five craft could be obtained on a call-up basis. In the two-person crew configuration, one subject was seated in front of each of these displays.

Crews were required to earn points by controlling the scout and four semi-autonomous “friendly” craft to locate and process valued objects within the simulated world. Crews had supervisory control over the friendly craft by entering strings of action commands via a text editor specifically designed for the task. The primary goals were to search the world for enemy craft to be destroyed and cargo to be loaded and taken to home base. Twelve cargo and 18 enemy craft (12 mobile, six fixed) were scattered throughout the world and only appeared on the map display after being sighted by craft radar (a 0.4-mi radius for the friendly craft and typically a 1.5-mi radius for the scout). The crews also had to manage the resources (fuel, missiles, cargo capacity) of each of the five craft. Each session lasted thirty minutes, although it could end prematurely if the scout was disabled by enemy craft or by collision with a tree or a friendly craft. Four different configurations of the forested areas and initial cargo and enemy craft locations were used.

Three experiments were performed [28], [21]. The first two were identical except for the manipulation of crew size. In each, five crews were run for 20 sessions. Large performance differences were observed between crews within the same crew size groups. From these two experiments, only data from the highest scoring one-person crew (Crew 1), and the highest scoring two-person crew (Crew 2), were selected for analysis for the modeling described here. The two best performing crews were chosen to obtain relatively stable behavioral data to support parameter fitting for process modeling. A detailed description of performance differences due to crew size appears in the companion paper [22].

Although Crew 2 scored more points than did Crew 1, this difference could not be solely attributed to crew size since one highly experienced one-person crew, the current first author (Crew E), could score as highly as did Crew 2. (Crew E
was estimated to have over 100 sessions of practice.) For the current modeling, then, data from three crews were chosen for analysis: Crews 1, 2, and E. Only data from the final eight sessions for each crew was used for model validation purposes.

C. Task Demands and Observed Behavior

The purpose of this section is to discuss some of the aspects of the task and observed crew behavior that motivated the theory of skilled human–environment interaction. The empirical evidence discussed below is a mixture of the results of statistical analyses of performance and a set of informal observations suggesting some hypotheses about the mechanisms underlying skilled behavior in this task.

The primary goal in the experimental task was to search the graphically displayed world with the scout and the four friendly craft under supervisory control to discover and process cargo and enemy craft. Discovered cargo remained displayed for the remainder of the 30-min mission and could be loaded at any time, although no points would be earned until the cargo were taken to home base. A considerable amount of latitude was available in determining how cargo should be processed. In some cases crews loaded cargo immediately upon discovery, and in other cases, crews left discovered cargo behind to be loaded at a later time. Sometimes, cargo were taken home immediately after loading, whereas in other situations, cargo were loaded, and then the loading craft was sent to continue searching for more cargo and enemy craft. There was some evidence to suggest that crews coordinated the activities of the scout (which had the largest radar range and was therefore capable of discovering the most cargo) with the friendly craft so that a friendly craft would be nearby to load any cargo that the scout had discovered.

Managing cargo processing was complicated by the need to handle threats from enemy craft. Twelve of the 18 enemy craft were mobile and would chase the friendly craft or scout upon discovery, often requiring crews to interrupt ongoing activities to respond to threats. After an enemy encounter, a craft might be made unavailable or a craft might not be able to return to its previously assigned duties due to a need to resupply missiles or fuel at home base. The availability of missiles could also influence which craft was used to load cargo because any loaded cargo were lost when a craft was lost. In addition, fuel expenditure rates were designed so each of the five craft had to refuel at home base at least one time during the middle third of the mission, and this requirement could be efficiently integrated to various degrees with the other demands to return to home base. Finally, all these strategic level factors could not be considered in isolation of the real problems associated with implementing these activities using both graphical and alphanumerical information displays, joysticks and horizontal and vertical autopilots for scout control, a text editor for assigning both current and planned command strings to the friendly craft, a cursor for assigning waypoint locations on the map, and a number of pushbuttons for enabling, aborting, and interrupting commanded friendly activity.

It also must be kept in mind that there was not much time for crews to determine control activities. This fact is made clear by considering the number of action commands that were entered via the text editor for friendly craft control. Crew 1 entered an average of 44.7 commands per session, Crew 2 entered an average of 67.4 commands per session, and Crew E averaged 51.7 commands per session. As a figure of merit, 50 commands per session corresponds to an action to change friendly craft activity every 36 s, on average. This figure does not include actions related to scout activities, which for Crews 2 and E consisted of manual control using joysticks to command locomotion through the partially forested world and for Crew 1 consisted of assigning waypoints with the map cursor and engaging and monitoring autopilot control. In addition, the time between control actions was not spent idly pondering information displays since many of the physical activities at the interface required to implement commands took considerable periods of time. For example, the observed times required to move the map cursor to specified targets (e.g., cargo) on the map display were estimated with Fitts’ Law approximations with intercepts of (2, 1, and 1 s) and slopes of (0.33, 0.15, and 0.15 s/bit) for Crews 1, 2, and E, respectively, and mean normal text editor session durations were observed to be approximately 9, 4, and 5 s for the three crews.

Despite the pace and complexity of task demands performance was reasonably successful, at least for Crews 2 and E. Considered together, these two crews on average managed each session to search more than 75% of the world area, discover more than 10 of the 12 available cargo, unload more than 85% of the discovered cargo at home base, and destroy more than 14 of the 18 available enemy craft. In addition, on average only one friendly craft was lost every two sessions, and neither crew had a craft run out of fuel in the eight sessions studied. The picture of required control behavior that emerged was one of action selection that was rapid and, at least in the case of Crew E, performed simultaneously or intermittently time shared with the scout manual control task that required (at least) perceptual-motor performance. The other two crews had more time to perform the action selection tasks (due either to the use of autopilot scout control or the presence of a second crew member), but neither of these crews exceeded the performance of Crew E. It is clear that Crews 2 and E were able to quite successfully meet the many demands of this complex task. As an introduction to the description of the modeling approach, the following sections briefly discusses a number of issues concerned with understanding skilled human behavior in task environments of such complexity.

D. Issues in Psychological Modeling

The findings above suggest some general, yet important, constraints on the design of an acceptable process model of skilled human–environment interaction. Due to the apparent complexity of the task, one modeling issue that must be given explicit consideration is how the human crews may have decomposed the overall task as a method of coping with complexity [50]. The challenge is to determine how crews might have decomposed the complex task resulting in minimal subproblem interactions: minimal either in that resolving these interactions was a manageable task in its own
right or minimal in that overall performance was relatively insensitive to any subproblem interactions left unresolved. A second critical modeling issue is to specify the nature of the information that the crews obtained from the environment to guide action selection, and the nature of the actions considered. Compounding the problems of identifying both perceptual and action units is the real possibility that these units are a function of experience level, as is suggested by studies of the hierarchical organization of skilled behavior (e.g., [35, 19]). If the decision processes underlying action selection are a potentially rate-limiting and error-producing step in information processing, an identification of the nature or "size" of the action units considered by the decision process is a critical step in achieving a model useful for performance prediction. A similar problem exists with regard to specifying the units of information perceived, because it may be that the skilled performer has a learned perceptual sensitivity to information initially unavailable to the novice (and perhaps the scientist) as in wine tasting [20] or in X-ray diagnosis [26]. In the laboratory task, the major source of available information was the dynamic graphical map display, consisting of irregularly shaped open and forested regions of two densities and a number of static and moving objects. Determining which of the potentially huge number of displayed relations constitute effective information appears to be a major issue in understanding performance in complex environments.

Finally, the dynamic nature of the environment also places important constraints on a process modeling approach. Note that in a dynamic world, both action and nonaction are equally in need of explanation, since in certain circumstances not acting may indeed be the appropriate way to achieve goals since the world changes state without the actor's intervention. Although the psychology of dynamic decisionmaking has received relatively little attention (but see [5]), understanding the nature of streams of behavior in a dynamic environment is an important problem. The theory presented in the next section is an attempt to address these and other critical issues in skilled human–environment interaction.

III. A Theory of Skilled Human–Environment Interaction

A. The Human–Environment System

A theory of human–environment interaction must be both a theory of the human and the environment. The environmental component of the theory specifies which features of the world are psychologically relevant to the behavior of interest and provides a descriptive language for representing these features. This descriptive language may represent only relatively simple, unstructured environmental features. On the other hand, this descriptive language may be more elaborate, in that it might represent complex environmental structure, such as in problem-space [33], or in decision-tree [40], representations. In all these cases, the language of environmental description is meant to reflect hopefully judicious choice over which features of the world are both relevant and irrelevant, psychologically, to the behavior of interest. Additionally, and perhaps more importantly, the selection of a language for environmental description may also place constraints on the nature of the processes that are taken to be necessary for the production of behavior. For example, problem-space environmental representations may promote viewing environmentally situated behavior to be the result of heuristic search processes, while decision-tree environmental representations may promote viewing behavior to be the result of comparative option evaluation and utility maximization.

Any psychological theory without a clearly specified environmental representation cannot be useful for design, for the theory provides no descriptive resources to allow cognition or action to be sensitive to environmental manipulation. As many human–machine systems researchers have suggested (e.g., [3, 48]), without detailed consideration of the task environment human behavior is simply too unconstrained to be effectively modeled. To be effective, therefore, cognitive engineering models need to make more reference to the environment than is typical of basic psychological research [45]. Knowledge of how the environment does constrain behavior, though, can sometimes simplify psychological descriptions by reducing the need to postulate complex cognitive accounts of structure in behavior that is largely a reflection of environmental structure [50]. These observations all suggest that a fruitful unit of analysis and modeling will be the human–environment system so that interaction can be seen to be mutually constrained by both cognitive and environmental factors.

B. A Perceptual View of Skilled Action Selection

The fluency and apparent economy of skilled human environment interaction, such as the behavior observed in the present experiments, motivates the assumption that often such behavior is perceptually selected based on information obtained from interface displays. The proposed framework for human–environment interaction has as its central assumption that through experience the human will gravitate toward a perceptual mode of action selection using interface displays as an external task representation. This transition to perceptual processing is assumed to be characterized by obtaining increasingly action-relevant information from the displays so that the skilled performer can be described as perceiving opportunities for action, rather than having to infer appropriate actions via problem-solving, decisionmaking, or planning processes. It is not assumed that the need for all such cognitively-intensive activity becomes obviated through experience. Rather, it is suggested that an analysis of the displayed information, which is made with reference to an explicit model of the external task environment, can indicate which aspects of behavior may not be adequately supported by the displays and may therefore require more complex cognitive activity.

The idea that goal-oriented behavior of considerable apparent complexity can be sometimes accomplished in a strongly perceptual fashion has some support within the cognitive science and artificial intelligence communities. In artificial intelligence, perhaps not surprisingly it is researchers in robotics, rather than in human problem solving, who have experimented with perceptually intensive processes for interacting with the
external environment (e.g., [6], [2]). These researchers cite the necessity of coping in a timely and appropriate fashion with the demands of dynamic, often uncertain, environments as a motivation for considering strongly perceptual approaches. Within the cognitive science community, researchers studying environmentally situated behaviors, rather than detached problem-solving, have also sparked a renewed interest in how perceptually oriented processing can sometimes produce behavior previously thought to require substantial amounts of elaborate planning and decisionmaking (e.g., [17], [29], [51], [57]; in addition, see [50] for a discussion of environmental sources of behavioral complexity). The present theory is an attempt to recognize the skilled performer’s attunement to rich sources of perceptually available information in guiding action selection.

C. A Framework for Environmental Description

The remarks of the previous two sections support the idea that an explicit environmental representation is a necessary part of any model of how environmental complexity may contribute to behavioral complexity. Also, this environmental representation should allow for a psychological description of some skilled behavior in terms of the perceptual selection of action. A number of existing forms of environmental representation meet the first requirement but not the second. For example, decision-tree and problem-space representations show how the structure of the task environment is reflected in behavior. However, these descriptions typically assume an internal task representation and complex inferential mechanisms, rather than perceptual action selection. On the other hand, stimulus-response descriptions of behavior characteristic of experimental psychology may be consistent with a description of behavior in terms of perceptual action selection. However, these descriptions do not typically capture any complex environmental structure to which the global organization of behavior must be sensitive. The purpose of the following section is to propose a language of environmental description that attempts to meet both requirements specified above: It should be rich enough to represent environmental complexity as it is reflected in the organization of behavior, yet it should remain open to the possibility that even complex activity can be perceptually guided.

Environmental Modeling for Skilled Behavior: Based on the assumptions outlined above, the environment in the present laboratory task was modeled as a set of dynamic affordance distributions. An “affordance” [15], [52] is a relationship between properties of the environment and properties of an organism’s action capabilities. An affordance is therefore a relational property that specifies the match between the environmental structure and the functional abilities of an actor. Although affordances are relational properties of the actor-environment system, once the appropriate relations are determined, the actor side of the relation can be left implicit and affordances can be used as a language of environmental description. For example, a relation between the strength of an actor and the weight of an object determines whether the object affords lifting. However, once the actor’s strength has been taken into account, the actor’s environment can be described in terms of lifting affordances, i.e., in terms of liftable and nonliftable objects. In this sense, the actor’s action capabilities define a frame of reference in which the environment should be measured and described.

What is the benefit of starting a modeling exercise by constructing an affordance-based environmental description? Perhaps most importantly, creating an action-oriented environmental model is a necessary first step in any task analysis that hopes to specify what cognitive activities are required for productive action selection (see [23]). Only with reference to such a model is it possible to examine the perceptually available information in order to identify sources of information capable of specifying the environmental constraints to which productive behavior must be sensitive. The presence of information capable of specifying the affordance structure is indicative of opportunities for the perceptual guidance of skilled action. The lack of such information, or its presence in a form incompatible with perceptual abilities, is indicative of the need for more demanding, post-perceptual cognitive activity. A task analysis based upon an action-oriented environmental model is therefore necessary to identify the nature of the perceptual and post-perceptual activities required for productive action selection. Only after such an analysis is performed can the modeler begin to address the issue of how such cognitive activities might be performed.

Affordances as Action-Oriented Environmental Differentiation: At a general level, then, the laboratory task environment was described in terms of regions that afforded searching, locomotion, loading, refueling, etc. This affordance-based description is intended to represent how the skilled performer may differentiate the environment for the purpose of efficient action selection. It may be the case that the differentiation of the environment provided by affordances may differ from a differentiation of the environment solely in terms of objects and properties perceptually obvious to a naive or passive observer. Thus, it is suggested that the skilled performer need not always first perceive obvious objects and properties and then use stored knowledge about these objects to infer action opportunities. Rather, the skilled performer is assumed to be capable of perceiving the environment as opportunities for action through an attunement to perceptually available information capable of specifying these opportunities. In this view, the environment is primitively differentiated by the degree to which various spatial regions support actions of various types. As a result, the structure the environment displays to a skilled performer is assumed to reflect properties of the performer’s own behavioral capacities [4].

A direct implication of this approach is that actors with differing abilities to act successfully in a domain (e.g., performers at different skill levels) may differentiate the environment along different dimensions since environmental differentiation is assumed to be action oriented. The psychologically relevant environments of differentially skilled performers may be comprised of different primitive entities. Rather than viewing the objects of expert experience to be constructed, or derivative upon the objects of naive experience, it may be productive in certain cases to consider how the expert employs an
alternate primitive environmental differentiation. The way in which the expert differentiates the environment might be best suited to the expert’s superior resources for action but perhaps ill suited to a performer without the expert’s behavioral repertoire. As will be seen below, the process modeling of human-environment interaction at different skill levels was accomplished by altering parameters not only in the cognitive component of the process model but in the environmental component as well. These manipulations to the environmental component of the model were intended to capture differences in the way in which different performers may have differentiated their environments.

The Dynamic Actor-Environment Relation: Affordances indicate the match between the action capabilities of an actor and the environmental structure. The relevant actors in the present task were the scout and the four friendly craft, as it was only through these agents that the crews could act upon their environment. This is a significant departure from the way in which affordances have typically been used by those studying human skills, where the environment is described relative to the physical and functional properties of the human body (e.g., [54], [55]). The nature of supervisory control, or interface-mediated performance in general, creates a situation in which the purely physical abilities of the human are of much less interest and importance than the extended set of functional abilities that the operator possesses through automation. In such tasks, automation, like a tool [15], [43], amplifies or extends the functional ability of the human and thereby expands the range of the relevant task environment beyond the interface. In the present task, crews could only act upon the environment using the functional capabilities of the five craft under their control. Therefore, the relevant affordances were considered to be relations between the structure of the simulated world and the functional abilities of the craft acting within this world.

In order to describe the simulated world as a set of dynamic affordance distributions defined over the available craft actions, the degree of match between the environmental structure and the action-capabilities of each craft were quantified. As this measure of compatibility can take on intermediate values, in the present approach affordances were not considered to be all-or-none entities. Rather, affordance values were used to indicate the degree of match between the environmental structure and the functional capability of each craft at each point in time. As Warren [56] has noted, as the match between the environmental structure and the actor’s action capabilities is varied, two qualitative features of the actor-environment system emerge. Warren has described these features as optimal points at which action is most efficient or most comfortable and as critical points that specify the boundary between phases in the actor-environment system in which different actions are most appropriate.

In relation to the present task, optimal points would correspond to the situations which are ideal for the selection of a given action, due to a perfect match between the environmental structure and the action capabilities of a friendly craft. For example, a situation in which a friendly craft is in the exact location of a cargo, the friendly craft has enough cargo-carrying capacity to load the cargo, and the friendly craft has enough fuel to load the cargo and take it home would constitute an optimal point with respect to the cargo loading affordance. Optimal points can be thought of as prototypical situations for taking a particular action. It is important to emphasize that the term “optimal” in this context means only that the environmental structure is maximally consistent with the taking of a certain action. Describing a situation as optimal for a particular action leaves aside the issue of whether the action is consistent with the performer’s goals in the environment. As will be seen below in the description of the cognitive component of the process model, the overall evaluation of action must be sensitive not only to the degree to which the environment is consistent with the action, but also to the degree to which an action is consistent with task goals.

Unlike optimal points which can be defined by examination of actor-environment relations with respect to a single action, critical points are a property of the entire set of affordances for a given actor. Each element in the set indicates the affordance value for a different possible action. With the simplification that the action will take the action with the highest affordance value, as the actor-environment system evolves, critical points specify the point at which a transition to a different action will occur. Critical points thus specify when the action that is currently most highly afforded differs from the action currently being taken, and a transition to the new action is required. In the process model, mismatches between current and most highly afforded actions resulted in what could be described as an “intent” to take the new action with the “goal” of reducing the mismatch between current behavior and the current environmental structure. As mentioned above, complications arise when it cannot be assumed that an actor will take the action whose affordance value is nearest its optimal point. A priority structure over actions in addition to affordance values may be necessary to measure the degree to which actions are consistent with task goals, and techniques may be required to resolve redundancies associated with multiple competing affordances relevant to achieving the same goal.

Informational Specification of Affordances: A possible difference between the present use of affordances and Gibson’s original conception is that it is not assumed that the detection of an environmental affordance is always “direct” or unmediated by any complex perceptual and/or cognitive processing. Here, it is taken to be an empirical question to determine whether there is sufficient information at an interface in a format available to perception to specify affordances so that affordance detection can be direct. In some cases in the present modeling, as to be described below, it did appear that there was sufficient information in the appropriate form so that relatively simple perceptual access to this information was sufficient to specify the existence of an environmental affordance. In other cases, relevant information did not appear to be available in a format so that simple perceptual detection of affordances was possible. In other cases, it appeared as if subjects substituted an easily perceptually detected affordance for one requiring more effort for detection to guide certain aspects of behavior.
Identifying Effective Affordances: Modeling Compromises:

Two compromises were made in order to implement the theoretical framework to model skilled behavior in the laboratory task. First, it would be an enormously difficult task to exhaustively describe all of the possible affordances existing in this complex environment. The functional capabilities that each of the craft were designed to have when creating the laboratory task determine only a subset of the affordances in existence in this environment. Crews could, and did, use the functionality of the craft in novel and unexpected ways. For example, the scout was given a capability of increased radar radius when above tree level so that a crew could more effectively search the simulated world. Due to the fact that an enemy craft would chase the scout when detected via radar, all crews discovered that by repeatedly bobbing the scout above and below tree level (to avoid being attacked), the radar capabilities of the scout craft could be used to draw an enemy craft toward the scout so it could be destroyed. Thus, scout radar, which was designed to give the crews the ability to gain additional information about the world, could be used to act on the world. This capacity for action was not intentionally designed into the simulation but rather emerged from the complex interactions between the functionality that was intentionally designed and the rich environmental structure and dynamics.

At least one crew was also observed to use radar to draw an enemy craft away from a defenseless friendly craft. The discovery and exploitation of this affordance appeared to have many of the characteristics of creative problem solving behavior, but an analysis of problem solving based upon an affordance-oriented environmental description is well beyond the scope of this paper. The environmental component of the present process model represents only those affordances apparently relevant to the skilled, fluent selection of action.

A second compromise made for the purposes of process modeling concerned the inability to specify adequately and exhaustively the information available from the graphical displays. It was assumed that the crews used this information to specify the existence of the environmental affordances. A comprehensive description of the environment would require not only a description of the task's deep structure in terms of affordances, but also a description of the task's surface structure in terms of displayed information (see [18]). The environmental description provided here was more complete in its identification of affordances than in the identification of the information available for affordance specification. As a result, the process model was able to successfully mimic crew behavior by directing actions to the affordances that were believed to be relevant to the crews, but the psychological description of how the crews may have detected the affordances using the interface information is incomplete.

IV. A PROCESS MODEL: ENVIRONMENTAL COMPONENTS

This section discusses the environmental components of the process model of skilled human-environment interaction in the laboratory task. First, the environment from the perspective of searching behavior is described. Here, the affordances relating to the crews' functional abilities to locomote and discover objects within the environment are defined. Second, the environment from the perspective of discrete action selection is described. Here, the affordances relating to the crew's abilities to load cargo, attack enemy craft, and resupply resources at home base are defined. Affordances for both the selection of current and planned actions are considered. Mechanisms representing action evaluation, selection, and implementation are presented in Section V.

A. Describing the Environment for Search Behavior

Fig. 1 is a depiction of one of the four world configurations as it appeared to subjects on the graphical map display. The open regions, which are indicated here in white, were displayed in light brown. The lightly forested and heavily forested regions, here indicated in dark gray and black, were displayed in light green and dark green, respectively. Only home base (the unfilled circle) and the initial location of the scout craft are shown in the figure, although the map display also indicated the locations of the four friendly craft and any cargo and enemy craft that had been discovered. The other three world configurations were similar, although the locations and shapes of the forested regions were different, and home base was in a different position in each world.

Searching the world for cargo and enemy craft with the scout craft involved two of the scout's functional abilities: locomotion and sighting objects with radar. Locomotion was most efficiently performed in open rather than forested regions due to the need to navigate around trees. Sighting objects, on the other hand, was most efficiently performed in lightly forested areas since the number of cargo and enemy craft per unit area was designed to be twice as great in light forests as it was in open regions or heavily forested regions. Determining the environmental affordances for searching behavior, therefore, requires describing the world in terms of the degree to which the structure of the world at each location

Fig. 1. Map display world representation showing open regions (white), lightly forested regions (light shading), and heavily forested regions (dense shading). These regions appeared in brown, light green, and dark green, respectively, on the laboratory display. Home base is shown as a large unfilled circle and the initial scout location is shown just above home base. This was one of four world configurations used in the experiments.
is compatible with both locomotion and sighting objects. The affordance of each world location for searching was considered to be a simple additive combination of the affordances for locomotion and sighting objects at that world location. In this way, the environmental affordances were considered to have a hierarchical or nested structure\cite{15}, \cite{53}. Affordances related to the coordinated activity of multiple actions (e.g., searching) were assumed to be analyzable in terms of affordances for each of the component actions (e.g., locomoting and sighting).

Fig. 2 shows the scout search paths generated in the same world by the two crews who used manual scout control (Crews 2 and E). The path for Crew 2 that appears in the figure was selected for illustration from the eight sessions considered in the analysis because it included a minimum number of deviations to process cargo and enemy craft. Such deviations were relatively common for Crew 2 and obscure the degree to which the route of the scout is indicative of the Crew’s desired search path. The path for Crew E that was selected for illustration was chosen because it was based on the same world configuration as was the path for Crew 2.

The purpose of describing the world with search affordance distributions was to attempt to understand how the search paths produced by human crews might be found to have a relatively simple basis once an action-oriented environmental description was considered. Fig. 3 shows the distributions of locomoting, sighting, and searching affordances as maps of the world in which the crew’s paths in Fig. 2 were created. Fig. 3(a) shows the world as it appeared on the map display. Fig. 3(b) shows the locomoting affordance, which is calculated by assigning a value of zero for open regions, a value of -1.5 to lightly forested regions, and a value of -2.0 to heavily forested regions. Darker regions on the map indicate higher locomotion affordances. The values for these affordances, and all of the world affordances discussed below, were determined where possible by constructing an objective measure of the degree to which relevant actions could be performed as a function of environmental conditions. The sighting affordances discussed in the next paragraph were determined in this manner. Where such a measure could not be efficiently constructed, the affordance values were determined by selecting values that seemed initially appropriate and then tuning these values by an iterative process of parameter fitting during the model validation process.

Fig. 3(c) shows the sighting affordances within the world. Again, darker regions on the map indicate higher affordance values. To construct this map, a 4-D vector was associated with each world location to indicate the percentage of area that would be covered by scout radar (radius = 1.5 mi) centered at that location that was open region, lightly forested region, heavily forested region and beyond the world boundary. For
each point, the inner product of this vector and a sighting
affordance vector is taken to determine the sighting affordance
of a world location. The sighting affordance vector was the
same for each world location and indicated the density of
cargo and enemy craft within each of the four types of
regions. The sighting affordance vector had a value of zero
for open regions and regions beyond world boundaries, and
a value of 1.0 for lightly and heavily forested regions. This
weighing scheme provides a simple measure of the amount of
forested area as a fraction of the total area covered by scout
radar. Maximum sighting affordances would exist, then, when
the entire scout radar range covered a forested region, and
minimum sighting affordances would exist when the entire
scout radar covered either an open region or regions beyond
the world boundaries. The graded structure of the sighting
affordance distribution results from the complex interaction
between the circular radar capabilities of the scout and the
irregularly shaped open and forested regions that determined
object density or, more generally, the interaction between the
crews’ action capabilities and the environmental structure.

Fig. 3(d) shows the distribution of searching affordances,
which are created by adding together the values of the loco-
motion and sighting affordances at each world location and
rescaling the values for clarity of presentation. Considered
three-dimensionally, this map indicates peaks and ridges of
high searching affordance and valleys and holes of low search-
ing affordance. The peak areas indicate the best compromise
between the conflicting demands for locomotion through open
regions and sighting objects in forested regions. (McHarg [31]
created maps in a similar manner for ecological planning of
highway routes). This action-oriented differentiation of the
environment was assumed to be a more psychologically rele-
vant environmental description for the purpose of attempting
to understand searching behavior than a description solely
in terms of perceptually salient objects such as forests. For
comparison purposes, Fig. 4 shows the locomotion, sighting,
and searching affordances for one of the three additional
world configurations used in the experiment. These maps were
constructed with the same procedure as described previously.

The hypothesis that searching affordances provided a psy-
chologically relevant differentiation of the environment for
search behavior was only indirectly assessed by considering
the degree to which this environmental description could
provide the basis for a relatively simple and empirically
adequate model of the process of search path generation. Long
range or global path planning consisted of selecting a sequence
of waypoints to be visited. The waypoints were defined to
be peaks and ridges in the searching affordance map and
other objects (e.g., cargo, home base) toward which scout
motion was opportunistically directed during the course of the
mission. Short range or local navigation through waypoints,
the other hand, consisted of simply treating all world
locations in the neighborhood of the scout to be the source of
an attractive “force” operating on the scout. The force
contributed by each world point was proportional to the search
affordance at the point. The current waypoint also contributed
an attractive force. The local movement trajectory of the scout
was thus qualitatively similar to the motion of a particle in
a gravitational field defined by one large point mass (the
destination waypoint) and a set of relatively small point masses
(the local search affordance structure). In this way, the scout
moved generally toward the destination waypoint, exploiting
local search opportunities along the way. An analogy would be
a shopper with the goal of visiting a department store at the far
end of a mall, who is nevertheless attracted to a variety of local
shopping opportunities along the journey. This method of local
navigation provided an extremely simple and efficient method
of constraining scout motion by environmental structure.

The hierarchical planning approach assumed that while the
detailed affordance map indicated the degree to which each
world location afforded searching, the local maxima on this
map were considered to be world locations that afforded
visiting for the purpose of effective search. Here, qualitative
properties of the affordance distribution for a long-term action
(searching) emerge to define affordances for a set of subactions
(visiting) to provide a possible decomposition of the original
searching task into a sequence of subtasks. This hypothesized
task decomposition, like the affordance structure upon which
it is based, is therefore a property of the interaction between
the human crews’ action capabilities and the environmental
structure, rather than solely a property of some internal
hierarchical organization presumed to underlie the crews’
action system. This example suggests that an action-oriented
environmental differentiation can, in some cases, provide the
basis not only for effective action selection via affordance
detection but possibly also for the hierarchical organization of
skilled behavior itself. However, it would be highly speculative
at this time to contend that a general approach to hierarchical
task decomposition could be constructed along these lines.

A similar set of affordance maps were constructed to
describe the searching affordances for the four friendly craft.
Unlike the continuous manual control of the scout, the friendly

Fig. 4. Set of affordance maps for another world configuration. (See the
caption of Fig. 3 for a detailed explanation.)
craft were commanded to search by positioning a cursor on the map display and entering a search command on the text editor. A friendly craft would travel along a line from its current location to the commanded waypoint, thereby searching along a linear path with width equal to twice the width of its radar radius (0.40 mi). The total sighting affordance associated with the selection of a waypoint was the sum of the sighting affordances along this linear route of travel. Sighting affordance maps for the friendly craft therefore had graded structure that in this case was due to the way in which linear paths emanating from a given friendly craft location would typically cover forested and open regions in an irregular fashion.

In addition to the sighting affordance component, the total searching affordance map for the friendly craft was also composed of maps indicating collision affordances, fuel-range affordances, and scout-coordination affordances. A world location was not considered to have a high search affordance as a potential waypoint if linear travel to the location would result in a collision with another craft. Therefore, an affordance map indicating waypoints that would result in collision was constructed. Another affordance map was constructed to indicate the elliptically shaped locus of points to which a craft could travel and still have enough fuel to return home for refueling. Finally, it was found that the search behavior of Crews 2 and E could not be successfully mimicked without the assumption that these crews were sensitive to the benefits of coordinating the locations of the friendly craft with the search path of the scout, most likely so that a friendly craft could be nearby to load cargo discovered by the scout craft. Thus, potential waypoints that would result in a period of spatio-temporal coordinated search activity for the scout and a friendly craft were identified to construct the scout-coordination affordance map. The total searching affordance of a potential waypoint was calculated by a simple additive and multiplicative function of the sighting, boundary, collision, fuel-range, and scout-coordination affordances. The point with maximum search affordance was selected as a waypoint in the process model.

It is important to note the process of identifying and quantifying search affordances for both the scout and the friendly craft was performed by identifying only the effective affordances: that subset of the entire set of affordances apparently relevant to searching behavior. The opportunities for action defined by these affordances were not always consistent with what appeared to be objectively optimal behavior. For example, the scout sighting affordance map was constructed by treating heavy forests as if they had the same high density of objects as did light forest, although object density in heavy forests was actually the same lower value as in open regions. Crews appeared to treat both heavy and light forests as if they had a higher object density than open regions. Thus, it appeared as if crews were not attending to the actual searching affordance structure present in the world. Note that the fact that crews may have erred in this fashion does not require that we abandon the notion that there was indeed an environmental affordance toward which their behavior was based. Their error apparently resulted from basing sighting affordance on readily available forest versus open ground information, rather than on actual object density information, which was not perceptually available. Whether the coloring of the map display with light and dark green forest regions contributed to this error is not known. Perhaps a more effective display would have been to create a direct mapping between perceptual information and the search affordance structure; that is, to show the search affordances directly as in Fig. 3(d).

B. Describing the Environment for Discrete Action Selection

The final set of world affordances concern the degree to which the dynamic structure of the task environment was consistent with the crews' abilities to take the discrete actions of loading cargo, attacking enemy craft and visiting home base. One of the primary reasons an affordance-based environmental description was selected was a desire to remain faithful to what appeared to be a significant degree of opportunism in the selection of these actions. It appeared, for example, that in many cases a craft would be sent home to refuel and resupply with missiles not because these resources were in short supply but because the craft happened to be traveling near home base. Stopping there to "top off" with fuel could be performed without a major disruption in ongoing activities. Similar comments could be made about certain cargo and enemy processing activities that were observed. Such observations led to the belief that a purely top-down or goal-initiated approach to the selection of action in this task was inappropriate for modeling observed behavior.

The motivation behind action selection in this task appeared to be a mixture of considering what behavior was desirable based on an assessment of task goals and what behavior was readily made available by the environment based on a perceptual assessment of world state. Affordances, as measures of the degree of match between environmental structure and the crews' action capabilities, appeared to provide a world description that was consistent with the high degree of opportunistic behavior observed in discrete action selection in this experiment. The psychological component of the process model to be described in the next section used a mixture of top-down (goal-based) and bottom-up (environment-based) factors in the selection of action. This mixture of opportunistic and goal-oriented behavior was achieved by combining affordance values with a priority structure to determine the control actions to be taken at each point in time.

Unlike the search affordance distributions that are defined continuously over world locations, the basis for the discrete action affordance distributions is the discrete set of world objects toward which actions could be directed. This set is comprised of the 12 cargo, the 18 enemy craft, and home base. Since there were five relevant actors (the scout and the four friendly craft), five distinct affordance distributions were constructed to represent the degree to which the world structure was consistent with the action capabilities of each of the five craft at a given point in time. Home base, for example, might differentially afford visiting for each of the five craft at a given time due to the different levels of fuel and missile resources of each craft as well as their different distances from home base and numbers of cargo aboard needing to be
unloaded. Affordances are always considered with respect to a given actor’s capacity for action and, in this experiment, capacity for action varied over time as a function of craft resources and location. The environmental structure also varied over time due to task dynamics, and therefore, features of both the actor and environment contributed to the requirement that affordance distributions be considered dynamic entities.

Fig. 5 depicts a set of affordance distributions for a typical world situation. Fig. 5(a) shows the world as it would have appeared on the map display. Cargo are indicated by C1 and C2 and were actually shown as numbered, solid gray circles. Enemy are indicated by R, O, and Y. R represents an enemy helicopter that was shown as numbered, solid red circle. O represents an enemy tank that was displayed as a numbered, solid orange circle. Y represents an enemy fixed emplacement that was shown as a numbered, solid yellow circle. The four friendly craft are shown here as F1, F2, F3, and F4, and actually appeared as numbered, solid blue circles. The scout, which is shown here as S, was displayed as a solid blue circle with the number zero. The complexity of this situation is representative of what might have occurred in an actual mission. In some cases, there were more cargo and enemy craft in evidence, and in other cases, there were less.

The set of affordance distributions in Fig. 5(b) portray the affordances in this world situation for both current and future discrete craft actions. Each row of three distributions indicates the affordances for a particular craft. Each column of distributions indicates the affordances at a particular point in an action-based, rather than time-based, planning horizon for each craft. The leftmost column indicates the current affordances for a craft, the middle column indicates the affordances that will exist at the completion of the current craft action, and the rightmost column indicates the affordances that will exist at the completion of the second craft action. The height of each line in each distribution indicates the degree of match between the environmental structure and the ability of the indicated craft to take the action specified under each line (e.g., going Home (H), loading Cargo 1 (C1), etc).

Affordances for future craft actions can only be determined if there is a sufficient degree of constraint so that future world affordances can be determined based on the current state and any current or planned craft actions. In the model, these affordances are determined only when a craft is committed to a particular action plan and therefore the future craft state can be predicted with reference to the plan. In cases where there is not enough information present on the display to specify future world affordances or where subjects have not become attuned to this information, it is probably the case that cognitive mechanisms of prediction will be required for the detection of future affordances. This issue will be discussed in the following section describing the cognitive component of the process model.

In the situation shown in Fig. 5, the scout has just sighted cargo C1 and C2 within the 1.5-mi scout radar radius. As can be seen in the leftmost affordance distributions, the cargo loading affordance for C1 is highest for craft F1. The other three friendly craft have lower affordance values for this cargo, indicative of the greater distances between these craft and C1. In this simplified example, it is assumed that all craft have enough fuel and cargo carrying capacity to load any of the available cargo. If either of these constraints were not met for a craft-cargo pair, the cargo would not be considered to afford loading by the friendly craft. Note that cargo C2 also affords loading for F1, but to a lesser degree than does C1, due to a distance effect. Many of the other craft also have affordance values for loading these cargo as well. In addition, each of the craft have affordance values for searching and going to home base, depending upon their amounts of fuel and missiles remaining, their distances from home base, and any cargo already aboard requiring unloading at home.
The second and third columns of the affordance distributions indicate the affordances for future actions that are possible to determine from constraints. Two types of constraints can be used to determine future affordances. One source of constraint is the nature of world dynamics. For example, if a craft is currently on its way to home base, the craft will have full fuel and missile levels at the completion of this activity. These levels, along with the other aspects of the environmental structure can be used to determine affordances for future actions. A second source of constraint on the way in which the environment changes over time is the crew’s own strategy to the extent that it is fixed or routinized. The overall degree of constraint underlying the dynamic behavior of a skillfully controlled system or environment is partially composed of constraint within the system itself and partially composed of constraint imposed by the fixed strategy for system control. In chess, for example, the first source of constraint is the rules of the game, whereas the second source of constraint is the “rules” of master level play.

It was assumed that crews were able to predict future affordances in the present task not only through attunement to environmental constraints but, in addition, through attunement to constraints supplied by their own fixed strategies for interacting with the environment. The manner in which the affordance distributions in the second and third columns of Fig. 5 were determined takes advantage, not only of the difference and differential equations underlining environmental dynamics but also of the constraints on environmental dynamics arising through the crews’ routinized policies for human–environment interaction. Craft F1, for example, has the highest affordance for loading C1 among all the available craft, and in addition the affordance for loading C1 by F1 is the highest affordance value of any potential action for F1. If the first condition did not hold, a craft other than F1 would be used to load C1. If the second condition did not hold F1 would be assigned some other action despite the fact that it might be the most appropriate craft to use to load C1. Since both conditions hold here, though, the fact that F1 will be used to load C1 can be used to determine future affordances. The affordance distribution in the second column for F1 indicates that at that time there will be a high affordance for loading C2, an affordance even higher than exists in the current situation. Since the relevant conditions mentioned above hold, F1 will be assigned to load C2. From this constraint, it can be inferred that when C2 has been loaded, home base will have a high affordance for visiting by F1, due to the need to unload these cargo.

Parameters in the model of the environment that determined numerical affordance values were initially determined by estimating the degree to which the environmental structure was consistent with each of the relevant actions. This process was performed by identifying optimal points in the match between a craft’s capabilities for action and the environmental structure. These optimal points indicated prototypical environmental situations in which taking a particular action would be most efficient. For example, the extremely high affordance values in Fig. 5 indicate craft-environment relationships that are near their optimal points, such as F1 loading C1, F2 attacking R, and F3 loading C3 as its second action. Optimal points for each action were considered to have equal numerical affordance values, regardless of the importance of the action from the perspective of the task payoff structure. This normalization was intended to separate the measurement of the affordance value structure of the environment from a psychological value structure that was assumed to reflect what actions were desirable in terms of task goals. Actual action selection in the model was performed by supplementing the affordance values with priority values that will be described in the following section. Thus, two factors were assumed to contribute to the attractiveness of a particular action: a) the degree to which the environmental structure afforded the action and b) the degree to which the action was desirable in terms of task goals. Highly desirable actions were not taken if they were not afforded by the environment, and highly afforded actions were not taken if they were not desirable.

Gradations and discontinuities in the affordance values were constructed as simple functions of whether or not various task constraints were met (e.g., missiles were required to initiate an attack; fuel was required to load a cargo) or the degree to which various task constraints were met (e.g., cargo loading is most efficiently performed by a craft that is near the cargo location; the affordance for visiting home is an increasing function of the number of cargo aboard needing to be unloaded). Some of these functions, like the sighting affordance, were grounded in relatively clear measures of the interaction between capacities for action and the environmental structure. Others of these functions were determined in a more ad hoc fashion. The affordance parameters were estimated by attempting to mimic actual crew behavior.

V. A PROCESS MODEL: COGNITIVE AND ACTION COMPONENTS

The cognitive and action components of the process model were intended to represent in a dynamic fashion how actions might have been selected via the affordance-based world description and implemented by human crews via the control interface. The cognitive-action components generating searching behavior were coupled to the searching affordance maps and used information from these maps as the basis for the construction of search paths. The cognitive-action components generating discrete action selection were coupled to the dynamic affordance distributions and used this information as the basis for the selection of discrete actions. In addition, the cognitive-action components for both searching and discrete action were integrated so that searching behavior and discrete action selection could be coordinated. First, the discrete action components of the model are described and then the searching components are presented.

A. Cognition and Action in Discrete Action Selection

The discrete action component was coupled to the dynamic affordance distributions. The model executed a series of 1-s iterations through a period of time representing a 30-min mission. Below, issues relating to both the evaluation and selection of both current and planned discrete action are discussed.
**The Evaluation of Action:** The affordance value of a particular action indicates the degree to which the environmental conditions are consistent with the action. A sensitivity to affordances thus represents one aspect of action evaluation in the model. However, affordances do not represent the degree to which an action is consistent with task goals. Therefore, a priority structure was used in addition to the affordance values to determine the attractiveness of each of the available actions at each model iteration. The combination of affordance value and priority value for a given action determined what will be called the appropriateness of a given action at a time. Here, appropriateness is considered to be a motivational variable indicating the degree to which a given action is desirable in a certain task situation. The appropriateness of a given action is a dynamic measure of both the degree to which the action is afforded by the environment and the degree to which the action is desirable in terms of task payoff. The priority structure gave greatest emphasis to defending a friendly craft from attack from enemy craft, for example, and relatively little emphasis to attacking fixed enemy craft that were worth relatively few points.

The manner in which the affordance values and priority values were actually combined to determine appropriateness values in the model can be seen from the following two examples. The appropriateness value (APP) for attacking a fixed enemy e by a given friendly craft f was calculated as a function of a priority value for this type of attack $P(\text{Fixed})$, and affordance values (AFF) for the friendly-enemy pair in the models of Crews 2 and E as

$$APP(f, e) = [P(\text{Fixed}) - P(\text{Fixed})] \times AFF(Dist(f, e)) \times AFF(\text{Fuel}(f, e)) \times AFF(\text{Miss}(f, e)). \tag{1}$$

In (1), $AFF(Dist(f, e))$ is an affordance value determined by distance between the friendly craft and the enemy, and $AFF(\text{Fuel}(f, e))$ and $AFF(\text{Miss}(f, e))$ are binary [0, 1] affordance values, indicating whether fuel and missile constraints would be satisfied in this enemy attack action. A priority value of $P(\text{Fixed}) = 0.85$ was used for fixed enemy craft, with the result that the maximum value of appropriateness of attacking a fixed enemy was equal to 0.85. This occurred when the component affordances were at their optimal points (zero friendly-enemy distance and fuel and missile constraints met). On the other hand, the priority value for cargo $P(\text{Cargo})$ was 1.0 to represent that loading cargo had greater priority than attacking fixed enemy craft. When the affordances for cargo loading were at their optimal points, the appropriateness for cargo loading reached its peak value of 1.0. The appropriateness value for loading a cargo c by a given friendly craft f in the models of Crews 2 and E was calculated as a function of cargo loading priority $P(\text{Cargo})$ as

$$APP(f, c) = [P(\text{Cargo}) - P(\text{Cargo})] \times AFF(Dist(f, e)) \times AFF(\text{Fuel}(f, e)) \times AFF(\text{Miss}(f, e)) \times AFF(WeightCap(f, e)) \times AFF(\text{Defended}(f, e)). \tag{2}$$

Here, $AFF(Dist(f, e))$, $AFF(\text{Fuel}(f, e))$, and $AFF(\text{Missiles}(f, e))$ are the same as above, and $AFF(\text{WeightCap}(f, e))$ indicates whether the weight carrying constraint was met, and $AFF(\text{Defended}(f, e))$ indicated whether the cargo was defended by a fixed enemy emplacement. In all appropriateness calculations for discrete actions, affordance values were confined to the range *[0, P(\text{Action})]*.

Note from the equations above that priority values and affordance values were not combined in a simple linear fashion in the calculation of appropriateness values. It was not clear that the available behavioral data were rich enough to allow the affordance- and the priority-based contributions to appropriateness to be independently identified in an unambiguous fashion. To do so would appear to require varying both affordance values and priority values (using manipulations of task goals) to identify, if possible, the independent effects of these two factors in the selection of behavior. Affordance values did change dynamically over time due to changes in craft-environment relationships, but task goals were kept relatively fixed in all of the experiments in this task environment. Task payoff structure was varied in the experiments, but as discussed in the companion article, this manipulation did not appear extreme enough to affect crew behavior.

Another source of difficulty in achieving a clear psychological interpretation of the constructs in the process model concerned the problems associated with identifying the information available from the graphical displays that could have been used to specify the existence of affordances. The central issue here is to determine the nature of the psychological processes that presumably were used to gain access to environmental affordances. In the present approach, the model does not specify the nature of the perceptual or cognitive processes that may have been used by crews to detect affordances from the available interface information. One avenue that is open, of course, is to interpret the functions used to measure the environmental affordances as cognitive information integration activities, or rules, that crews may have used to estimate affordance values from system state variables. This approach would give these functions a psychological interpretation. However, there was no evidence that crews perceived state variables (rather than action opportunities) and used such rules (to infer action opportunities from state variables). Also, in the case of Crew E, there was some evidence to suggest that such rules were not used. This evidence concerned this crew's ability to skillfully perform an entire session without error, while calling up status information (fuel, missiles carried, cargo carried, etc.) only five times per session on average. A more complete account of behavior in this task would supplement the present model with mechanisms showing how displayed information could be used to specify affordances, although describing the information available in perceptually rich situations is a very difficult problem.

**The Selection of Current Action:** In the majority of model iterations simulating crew behavior, no additional processing beyond updating the affordance distributions in the environmental model was required, as the state of the environment had not changed sufficiently so that new actions were indicated. In many of these iterations, though, the model was not idle but
rather performing control activities (editing, pushing buttons, controlling scout motion) related to implementing actions that had previously been selected. In iterations in which the state of the environment was such that current activity was inconsistent with the most appropriate activity, the model would attempt to take an action with the goal of bringing activity in line with the environmental state and task priority structure. Such inconsistencies were most often the result of detecting a new cargo or enemy craft or when a craft had completed an action and the next action in the planning horizon required implementation.

Even when new actions were required, in the majority of cases, little internal processing was necessary other than detecting that a new action was required and activating a hierarchically arranged set of action mechanisms. Whether or not more internal processing was required depended on whether or not a conflict was caused by the fact that two or more redundant actions were suggested by the appropriateness values. Redundant actions are actions directed toward the same goal (e.g., loading a given cargo). The affordance distributions reflect craft-environment relations and result in a problem decomposition along craft-oriented lines. Subproblem interactions can exist when more than one craft share the same most highly afforded action. In such cases, the craft with the highest appropriateness value was assigned the action, and the appropriateness values for the each of the other craft competing for the action were nulled.

The Selection of Planned Action: The dynamic affordance distributions represent not only current affordances, but also those that will exist at future stages in each craft's planning horizon. A high affordance may exist, for example, for a particular craft to load a particular cargo as the second action in the craft's planning horizon, perhaps because the craft's location at the termination of the current action may leave the craft nearby the cargo. Attunement to affordances for future actions is assumed to be possible through the use of visual imagery, i.e., by imaging the friendly craft to be in its expected position at the termination of its current activity. Thus, we assume that the performer need only image the craft to be in its expected future location, and some of the same perceptually oriented mechanisms capable of detecting the affordances based on its current location can be used to detect the affordances that will exist based on its imaged location. Klein and Crandall [24] have advanced a similar view of imagery-like, or simulation-based, planning mechanisms:

In our view, one of the most important and powerful features of mental simulation is that it provides a means of planning and evaluation that is perceptually based, rather than requiring abstraction from an analysis of an event. People are able to experience a situation "as if" it were occurring and use their perceptual-recognitional abilities to understand how they might respond to it. The affordances recognized in the simulated event are experienced and evaluated in terms of decisions and plans of actions that "could be" initiated. Mental simulation allows the decision maker to assess the affordances provided by the particular imagined situation. (pp. 34-35)

The central assumption underlying our imagery-based approach to modeling planning is that some of the knowledge underlying skilled behavior is highly context-bound and encapsulated within the perception-action mechanisms governing interaction with the external world. The fluency of such behavior, it is suggested, may come at the price of limited access to this knowledge for the types of flexible reasoning often postulated in cognitive models of planning. Imagery is therefore postulated as a mechanism for gaining access to perceptual knowledge (see also [25], [44], [46]) in the present case though a process of imaging a future environmental state and using perceptually oriented mechanisms to select actions from the imaged description. A chess player imaging a piece to be in a new position, or a person imaging interaction with a touch-tone telephone to recall a frequently dialed but difficult-to-report number may be other cases in which it might be supposed that some of the knowledge underlying skills is perceptually encapsulated and that imagery is used to extend the applicability of this knowledge to situations beyond actual interaction with the world. Although the psychological validity of this view needs careful testing, this perception-imagery based method of planning represented a relatively simple and efficient method of implementing the selection of future actions in the process model, since the same perceptual mechanisms used to assess current action opportunities could also be used to assess future opportunities from the predicted world state.

B. Cognition and Action in Search Behavior

Cognition-action components for the production of searching behavior were coupled with the affordance-based environmental representation as depicted in Fig. 6. At the start of a session, the model identified the peak areas in the search affordance map as candidate waypoints points to be visited during the session. These peaks were submitted to
a generate-and-test mechanism that attempted to order the waypoints in the most efficient manner possible with respect to the constraint to minimize backtracking through previously searched regions, and the constraint that home base be visited once during the middle third of the mission for refueling. The output of this mechanism was an ordered list of scout waypoints. The first waypoint was then selected and the waypoint itself was considered to possess a visiting affordance. The scout did not fly in a linear path to the waypoint, though, because scout motion was determined not only by the visiting affordance but also by the local search affordance structure in the immediate vicinity of the scout.

Efficiencies resulting from the affordance-based environmental description were even more evident in the local (interwaypoint) path-generation method. Detailed motion commands for the scout were generated by considering the searching affordance distribution to be an attractive force field, which when combined with a force exerted by the visiting affordance of the current waypoint, determined the direction of scout motion on a second-by-second basis. Large weights on the local searching affordance values relative to the weighting on the visiting affordance exerted by the current waypoint resulted in meandering scout motion that was very sensitive to local search affordance structure. In contrast, a large weight on the visiting affordance relative to the local search affordances resulted in a direct path to the current waypoint that largely disregarded the local search affordance structure.

C. The Implementation of Action

Fig. 7 shows the hierarchically arranged set of action mechanisms that were used to simulate the physical control activity at the interface necessary to implement actions for the scout and friendly craft. The mechanisms at the top of the diagram are responsible for managing the flow of information to the lower-level mechanisms that actually simulate observable control activity and also for coordinating physical activities that require multiple action mechanisms. Hierarchically controlled action mechanisms have been proposed by many behavioral scientists to describe the organization of skilled action [13], [19], [30], [35], [37]. In such models, the lower-level mechanisms are assumed to possess a degree of autonomous control of action which does not have to be controlled at higher levels.

In the figure, the links between the mechanisms denote information flow, which is assumed to be always in the downward direction. For example, the highest level action mechanism is activated each time any interface activity is required, and based on whether the need for action concerns the friendly craft or the scout, this mechanism sends information downward to the appropriate mechanism at the next lower level. Although information always flows downward in this component of the psychological model, an implicit upward flow of information does exist through the external environment; that is, the results of actions performed by the lower level mechanisms can become known to the upper level mechanisms through the perception of the environmental changes caused by those actions.

The most general action mechanism at the top of the hierarchy is responsible for scheduling the possibly competing demands for scout- and friendly-related interface activity. At each iteration, all commands for action sent by the action selection mechanism are executed in order of their appropriateness.
values. After one of the three scout action mechanisms or one of the five friendly action mechanisms has been activated, it in turn determines which of the interface activities defined by the next lower level action mechanisms is required. These mechanisms, then, activate the physical action mechanisms at the lowest level to enter commands in the friendly craft text editor, manipulate the map cursor for waypoint entry, press pushbuttons to provide real-time modification of friendly craft activities, control the scout autopilot, and control the joystick used for manual scout control.

As was discussed previously, the crews differed in the way in which they interacted with the interface controls, so some of the action mechanisms had to be individually tailored to mimic the behavior of each crew. Crew 1, which is a one-person crew, used the autopilot for scout control, whereas Crew E, the other one-person crew, used manual control for locomotion of the scout that was intermittently interrupted by editing sessions for friendly craft control. For Crew 2, which is the two-person crew, one member was dedicated to the task of scout manual control, whereas the other member was dedicated to the task of friendly craft control.

VI. MODELING INDIVIDUAL CREW BEHAVIOR

The process model of human-environment interaction was evaluated by selecting parameters to fit the behavior of each human crew and then using the model to mimic each crew’s behavior. The sections below describe both model parameterization and the results of the model evaluation tests.

A. Model Parameterization

Model parameters that were manipulated to mimic crew behavior with the process model concerned the affordances to which behavior appeared to have been directed, the priority structure over various actions used to determine appropriateness values, parameters in the action mechanisms that determined the policies for interface manipulation, and the time required for various interface control behaviors to be executed. In addition, the planning horizon was also manipulated in an attempt to mimic crew behavior, but the effects produced by planning more or less than three actions (see Fig. 5) were not consistent with any observed differences between the three crews. One final parameter that was manipulated was the time assumed to be required for the crews to update appropriateness values based on the displayed world state.

The first step in the model parameterization process was to construct a set of 22 summary performance measures to determine a performance profile of each crew, as described in the companion paper [22]. These measures revealed intercrew differences in searching behavior, the numbers of objects discovered, the way in which the objects were processed, and a variety of additional performance differences. The formal component of the empirical model validation process consisted of creating a model of each crew that produced behavior consistent with the crew’s performance profile, as measured by a lack of statistically significant differences between each of the 22 crew- and model-produced measures of performance. Eight sessions of data were available for each crew, and each crew model was executed for eight sessions as well using the same world configurations as seen by the crews. Since a lack of statistically significant difference between crew and model performance can occur due to high variance as well as near equality of means, an additional and more stringent model validation procedure was created. In this test, the performance produced by the three crew models was examined to determine whether the statistically significant differences between the three models corresponded to the statistically significant differences between the performance of the three crews. In the following, the individual tests of crew-model correspondence will be termed similarity tests, whereas the tests of whether the models mimicked inter-crew differences will be termed configural tests.

Parameter fitting was performed by an iterative process using both the performance profiles and informal observations of crew and model behavior as measures of model adequacy. Both crew- and model-produced data could be used to construct a dynamic replay of each session on the map display. Sessions could be replayed slower or faster than real-time, and the spatial and temporal patterns available from these graphical replays were difficult to quantify, but were nevertheless important in guiding the parameter selection process.

In terms of the affordance parameters, manipulations were made in both the searching and discrete action components of the environmental representation. For searching behavior, both the environmental models for Crews 2 and E were parameterized so that scout and friendly craft searching behavior would have spatio-temporal coordination, whereas the model for Crew 1 did not coordinate scout and friendly craft search paths. Thus, it was assumed that Crew 1 did not detect the opportunity for coordinating these paths, but the other two crews did detect this affordance and achieved the benefits associated with having a friendly craft nearby to process cargo and enemy craft discovered by the scout. For discrete action affordances, parameters were adjusted to reflect that both Crews 2 and E detected and exploited the opportunity for attacking fixed enemy craft with the friendly craft while Crew 1 did not exhibit this behavior, most likely because Crew 1 had little success early in practice in getting the friendly craft to successfully attack fixed enemy craft. This is a clear example where the modeling approach allows the environmental representation to be sensitive to differential abilities to productively act within a domain.

Regarding cargo processing, affordance parameters were adjusted to remain consistent with the observation that Crew 1 often used the scout to load cargo, whereas Crew 2 used the scout for cargo loading less often, and Crew E rarely used the scout for cargo loading. Finally, the model of Crew 1 was also parameterized differently than the other two models with respect to the home affordance parameter because the home affordance for this crew appeared to be strongly affected by the ability to unload previously loaded cargo. Thus, the Crew 1 model exhibited a predominantly serial cargo processing strategy of taking loaded cargo immediately to home base, whereas the other two models sometimes allowed friendly craft carrying cargo to be used for other activities, depending
on the overall affordance structure. At a general level, the main difference between the Crew 1 model and the other two models in discrete action selection was that the Crew 1 model was parameterized to treat the scout craft much as if it was simply an additional friendly craft, whereas action selection in the other two models was sensitive to the functional differences between the scout and the friendly craft. It was hypothesized that Crew 1’s apparent insensitivity to the functional differences between the scout and friendly craft (and thereby an inability to exploit the scout’s superior searching abilities) may have been a problem simplification strategy, allowing a single set of decision-making policies to govern both scout and friendly craft activity.

A parameter was used to represent the time assumed to be required for updating the appropriateness values based on viewing the displays. The best fits to observed behavior were obtained by assuming Crew E updated these values in 0.5 s, Crew 2 in 1.0 s, and Crew 1 in 3.0 s. This parameter had a dramatic effect on model performance, as it determined the degree to which the actions considered most appropriate within the model lagged behind changes in environmental opportunities.

Finally, a number of parameters within the three models’ action systems were adjusted so that control activities were consistent with the observable behavior of each crew. Most importantly, the action system of the model of the two-person crew, Crew 2, was designed so that control activities for both the scout and friendly craft could be performed in parallel because this crew was observed to dedicate one member to friendly craft control and the other member to scout control. In contrast, the models of Crews 1 and E were constrained to perform scout and friendly craft activities serially. In addition, the model of Crew 1 used the autopilot for scout control to mimic this crew’s behavior, whereas the model of Crews 2 and E used manual control of scout locomotion. Finally, a number of parameters were adjusted to reflect the fact that Crew E was most proficient at physical interface manipulation activities, whereas Crew 2 was slightly less proficient and Crew 1 was least skilled. These parameters indicated times for moving the map cursor (as modeled using Fitts’ Law), pressing buttons, and the time to enter commands using the friendly craft command editor.

B. Empirical Adequacy

The ability of each of the three models to mimic crew behavior was assessed by using the same 22 measures used to describe human crew behavior to describe model behavior (see [22]). As mentioned above, similarity tests were used to test whether model and crew performance significantly differed on a particular measure, whereas configurational tests were used to test whether a given pair of crew models was able to replicate the performance differences on a given measure observed between the pair of associated crews. In total, there were 66 similarity tests (three crew-model pairs each using 22 measures), as well as 66 configurational tests (three crew-craft and corresponding model-model pairs each using 22 measures). All statistical comparisons were conducted at \( t \) tests at the 0.05 level of significance.

In 58 of the 66 similarity tests model and crew performance were not significantly different. All crew models satisfied tests associated with points scored, discovering cargo and enemy craft, and successfully processing cargo and enemy craft. All tests associated with the differential usage of the scout and friendly craft pertaining to these measures were also satisfied. On the other hand, the models failed to achieve consistency with crew performance on eight of the 66 measures. (About three failures would be expected due to chance if the measures were independent: 66 tests \( \times 0.05 \alpha \) level. More failures would be expected if the measures were not independent.) Of these failures, one occurred for the model of Crew 1, three occurred for the model of Crew 2, and the model of Crew E failed on four performance measures.

For analysis of the results of the more demanding configurational tests, four types of test results were defined. A “hit” was defined as an agreement in the comparison tests for each pair of crews and the associated crew models on a particular measure. For example, if Crew 1 sighted less cargo than Crew 2, and the Crew 1 model sighted less cargo than the Crew 2 model, this test result was scored a hit. Another type of hit is when neither the crews nor the associated models differed on a measure. A “miss” was defined as a difference exhibited between a pair of crews on a measure that was not exhibited by the associated pair of crew models on that measure. A “false alarm” was defined as a difference that was found between a pair of crew models that was not exhibited by the associated pair of crews. Finally, a “reversal” was defined as a case where crews differed in one direction on a measure, whereas the associated pair of crew models differed in the opposite direction with respect to that performance measure. Of the 66 configurational tests, 54 were hits, five were misses, six were false alarms, and one test resulted in a reversal. Fig. 8, for example, depicts the mean number of points scored per session by the three human crews and the three models. With regard to this single overall performance measure, each of the three crew models successfully mimicked the behavior of its associated crew, and the pairwise comparisons of model performance mimicked the pairwise comparisons of crew performance (no significant differences were found between the performance of each model and its associated crew, and the models of Crews 2 and E both scored significantly more points than did the model of Crew 1, just as Crews 2 and E both scored significantly more points than did Crew 1).
level as Crew 2 can in large part be accounted for by the simple fact that Crew E could fly the scout, enter friendly craft commands, and identify environmental affordances slightly faster than could Crew 2. There were very few affordance parameter differences between the Crew E and Crew 2 models, and those that did exist did not contribute significantly to the ability of the Crew E model to perform as well as the Crew 2 model. Model performance was extremely sensitive to the parameter that indicated the time required to update the appropriateness values from the world display. The dynamic nature of the task tended to cascade and thereby amplify the negative effects of such delays. As a result, the model would soon get far behind the dynamic environment in its selection of control activities.

In addition, the modeling appeared to demonstrate that Crew 1's inability to differentiate between the scout and friendly craft contributed to this crew's relatively poor performance. Nearly the same set of affordances were used to guide both scout and friendly craft activity in the model of Crew 1, whereas the models of the other two crews guided scout activity toward a quite different set of affordances than were used to guide friendly craft activity. These affordance parameter manipulations resulted in the Crew 1 model's insensitivity to the functional differences between the scout and friendly craft. For example, Fig. 9 demonstrates that Crews 2 and E did not make significant use of the scout to process cargo, but Crew 1 was just as likely to load any piece of cargo with either the scout or a friendly craft. Although both the scout and friendly craft were equally able to load cargo, the scout had a much greater ability to discover cargo due to its greater radar radius. By exploiting this functional difference between the scout and friendly craft, Crews 2 and E could dedicate the scout primarily to the task for which it was best suited (searching) and could thereby discover more cargo for friendly craft to load and take to home base to score points.

In conclusion, the parameterized models were reasonably successful in mimicking skilled human behavior in this dynamic and uncertain environment. The modeling results provided illuminating information concerning task demands and strategic behavior and demonstrated the sufficiency of the proposed theory in a complex behavioral situation as well.

VII. DISCUSSION

A. Conclusions

The process modeling of skilled behavior in this laboratory task demonstrated the sufficiency of the proposed theory of human-environment interaction as a candidate framework in which to describe human behavior. This research demonstrated two important ways in which taking the human-environment system as the unit of analysis can be a beneficial approach to the study of rich behavioral situations. First, by constructing the overall model as a pair of highly interactive environmental and cognitive components, both environmental and cognitive factors could be shown to provide mutual constraints on the selection of behavior. Second, using the human's behavioral capacities as a frame of reference for environmental description resulted in an action-oriented differentiation of the environment suggestive of how the skilled performer might

Fig. 8. Graph of crew and model performance on the measure of mean number of points scored per session.

Fig. 9. Graph of crew and model performance on the measure of mean number of cargo unloaded per trip to home base by the scout and by each friendly craft.
perceive and conceive of the world for the purpose of guiding skilled activity.

These two features of the proposed theory both contributed to creating a relatively simple account of the mechanisms underlying skilled behavior in this task. Any instance of skilled human–environment interaction is constrained by both environmental and cognitive factors. Unless the relevant environmental constraints on behavior are explicitly represented in an external environmental model, a cognitive model will by necessity have to contain an internal representation of all relevant environmental constraints for its behavior to be productive. On the other hand, if environmental constraints are explicitly represented in an external model, it then becomes possible to examine the perceptually available information to determine which of these constraints might be perceptually detected, rather than cognitively represented in a more abstract manner. It may well be that certain environmental constraints must be abstractly represented for behavior to be productive in some situations, perhaps due to restricted or impoverished perceptual access to relevant information. It seems highly unlikely, though, that all such constraints must be so represented, especially when the potential richness of the available perceptual information is taken into account, and when considering the intimate perceptual-environmental relationship characteristic of so much fluent, skilled behavior.

Viewing skilled behavior in the laboratory task within this framework allowed for a partial identification of the way in which the graphical displays may have both positively and negatively affected human performance. On the positive side, the rich graphical displays appeared to provide an effective external task representation that allowed certain environmental constraints on behavior to be perceptually detected. On the negative side, it appeared that in certain cases no support was provided for the perceptual detection of constraints, and in other cases the displays may have created a misleading mismatch between the depth structure of the environment (the affordances) and the surface structure (the displayed information). For example, fuel range, the distance that could be covered with remaining fuel and still permit a return to home base, was one constraint to which craft activity had to be sensitive. However, no displayed information was directly available that would have allowed the perceptual assessment of the consistency of behavior with this constraint. Rather, crews had to cognitively estimate fuel range using both displayed information (fuel remaining) and knowledge of task dynamics (fuel consumption rates). Visually displaying fuel range directly with ellipses as was done to construct the searching affordance map might have allowed the fuel range constraint to have been perceptually assessed. In other cases, such as in scout searching behavior, displayed information for the perceptual selection of action was available. However, based on the present data it is uncertain whether the forest color coding contributed to subjects’ inaccurate estimation of search affordances.

Finally, this research demonstrated the importance of giving explicit consideration to the demands associated with interacting with a dynamic environment. The model demonstrated that the negative effects of any delays in maintaining the consistency of behavior with the rapidly changing environmental structure became cascaded and amplified as the human–environment system evolved over time. Stopping to ponder a wide range of alternative actions in the hope of achieving an optimal course of activity is simply not a viable strategy in certain dynamic situations. Also, the appropriateness of any action is not a context-free attribute of that action but must instead be seen as a collective function of both goal- and environmental-centered factors. Both these factors contribute to the evaluation of action in an integrated, dynamic fashion.

B. Implications for Psychological Modeling

Considering its combined theoretical-empirical nature, the present research should perhaps be seen as more successful in suggesting a number of hypotheses for further study, rather than in demonstrating any particular fact about cognition and behavior. This point conceded, it is probably also the case that this attempt at comprehensive but possibly shallow psychological modeling, rather than narrow but deep, required that a number of architectural issues be addressed that might never had been considered otherwise. As Pylyshyn [39] has noted, the manner in which psychological processes are often decomposed for methodological purposes and individually researched may have the potential to hide how these supposedly distinct psychological abilities contribute to the generation of realistically complex behavior. The challenge of providing a comprehensive psychological model of behavior in the present experiments forced detailed consideration of a number of system-level architectural issues. One result of this focus was that certain aspects of cognition were viewed to function quite differently when seen within the overall context of guiding action; then these aspects would perhaps be viewed if considered individually and without a focus on productive interaction with the external world.

Perception is one such example. This research suggests that the way in which perceptual system is modeled will be strongly dependent on the behavioral context in which perceptual abilities are studied. If the behavior of interest is how a person might describe or recreate from memory, a particular perceived situation then it may be natural to view the central role of perception to be assisting in the construction of internal environmental descriptions involving structural relations perhaps not directly relevant to action. Here, perception is primarily viewed as serving a descriptive function with no essential relation to the guidance of activity. On the other hand, if perception is considered in the context of dynamic interaction with the world as was the focus of the present research, the central role of perception may be to select information from the environment to efficiently guide ongoing activity. Perception may of course serve both descriptive and action-oriented functions [32], and the important implication for psychological modeling is that the potential for both perceptual forms must be considered when modeling any instance of action selection.

A common strategy in cognitive modeling is first to provide a representationally intensive account of how some complex
behavior might be accomplished and to thereby assume (either implicitly or explicitly) that perception's central contribution to behavior is to construct the cognitive representation via processing external information. The functionality of perception is then defined by a theory of planning, problem solving, decisionmaking, or the like. However, our research suggests that considering perception from the perspective of action selection is important when modeling human-environment interaction of any realistic complexity. We suggest that one begin with an environmental model that specifies the action structure of the environment (i.e., affordances) as well as an environmental model that specifies the structure of the perceptually available information (see [23] for a task analysis framework based on models of environmental action structure and perceptual structure). It is possible that the perceptual information may be rich enough to specify many if not all of the relevant details of the action structure. In such cases, a perceptually intensive approach to modeling action selection might be appropriate. In other cases, the available information may only partially specify the action structure. Here, perception may also perform the descriptive function of assisting in the construction of a cognitive representation that is more elaborate and informative than the information presently stimulating the perceptual system. The role of the representation will be to ensure that action selection is consistent with those additional environmental constraints that cannot be perceptually assessed.

On a related theme, although the present research did not attempt to describe the skill acquisition process, our description of skilled behavior may have some implications for modeling the acquisition of environmentally situated skills. Many, if not most, current models of cognitive skill acquisition are based on the assumption that the environmental information obtained by a performer remains fixed through experience, but that skill is acquired through the use of increasingly efficient cognitive abilities to process this information. For example, Logan [27] provided a theory whereby action selection is made increasingly efficient through the accumulation of memories for previous task encounters, and Anderson [1] has provided a theory whereby action selection becomes increasingly efficient due to the proceduralization and chunking of knowledge. These theories might both describe important aspects of the skill acquisition process, but the present research suggests that the acquisition of skill might also be enabled by the performer's ability to select increasingly relevant action-oriented information from the environment.

As Dawes [8] and Dawes and Corrigan [9] have observed in their reviews of the judgment literature, expert judgment behavior appears to rely heavily on the ability to select and encode the most highly diagnostic environmental information. The fact that even very simple linear models often provide successful behavioral accounts of expert judgment behavior is claimed by these researchers to indicate that the expert possesses a superior ability to identify the relevant environmental information but that abilities to integrate this information are quite limited. Similarly, the primary reason that the present process model could successfully perform this challenging task was that the input information provided to the model was carefully selected through an intensive study of the task environment and the behavior of human crews.

C. Comparisons with Other Modeling Approaches

Conceiving human activity to be oriented toward a dynamic affordance structure represents a relatively new way of describing complex behavior, at least as far as human performance modeling is concerned. Within the human performance modeling tradition, discrete action has typically been conceived as being the product of some type of enumerative process, such as the comparative evaluation of options with respect to a utility function, or the search through a problem space for an action sequence to reach a goal state.

It must be emphasized that the present modeling differs from these previous approaches only with respect to issues of necessity but not sufficiency. There is no claim that rationalistic methods of action selection could not have been used to model performance in the present task, or in any task for that matter. The great appeal of such methods is their sufficiency: nearly any, and perhaps all behavior can be construed to be the result of either utility maximization or problem space search. An important issue, however, is to understand those conditions in which these resource-intensive processes will actually be necessary for effective performance. The present theory is simply an attempt to recognize that in some cases even apparently complex behavior can be produced via the perceptual identification and selection of action, without resort to highly enumerative strategies. Without this insight, there may be a tendency to identify behavioral complexity with some similarly complex, perhaps rationalistic, method of action selection. The unfortunate result would be that performance models would continue to be incapable of representing the distinction between the perceptually oriented processes that underlie fluent skills and the more cognitively demanding and resource-intensive processes that underlie less fluent behavior.

In the present theory, an environmental model that represents the constraints upon productive action as well as the information capable of specifying these constraints is constructed. By then using this model to assess opportunities for the perceptual selection of action, the present approach provides a method for tentatively identifying when cognitively intensive processes will be both necessary, and unnecessary, for effective performance. As was demonstrated above, in the present modeling, it was found that in some cases, problem space search did appear to be necessary (e.g., in the selection of a global search plan), and in other cases, the comparative evaluation of alternatives did appear to be necessary (e.g., in conflict resolution among discrete actions). However, in other cases it was found that displayed information was available to enable a simpler perceptually oriented mode of action selection. To summarize, the present approach should not be seen to be at odds with previous human performance modeling approaches, but rather complements those approaches by identifying the conditions under which they may and may not provide faithful accounts of the processes underlying skilled activity.
D. Implications for Interface Design

The present study is not the first to explore the application of principles from ecological psychology to the design of human–machine systems (e.g., see Flach, [12] and Vicente and Rasmussen, [53]). As discussed by Flach, Gibson’s own studies of human–environment interaction in aircraft and automobiles had an important influence on his development of the ecological approach to perception. One reason that concepts from ecological psychology may relate well to the field of human–machine interaction is that both disciplines take the view that the human–environment system is the appropriate unit of analysis and modeling.

At a gross level, there are at least two general strategies for aiding human control behavior in human–machine systems. The first is to provide the operator with a more effective representation of the environment through the use of computer generated, possibly graphical, information displays. The second is to provide the operator with a computer-based assistant, possibly based on artificial intelligence technology, which helps the operator determine an appropriate course of action. The first strategy focuses on improving the nature of the information available to the operator, while the second focuses on improving the operator’s ability to use the available information to determine control actions. Both strategies for aiding have as one major goal to reduce the demands and errors associated with the effortful cognitive activities required of many operators of currently designed human–machine systems.

The present research emphasizes the importance of understanding why cognitive demands are present, prior to determining a strategy for aiding the operator in meeting these demands. The present modeling suggests that cognitive demands can result from displays that do not adequately support the perceptual selection of action. At a general level, the proposed view is that many of the effortful and error-prone cognitive activities required of operators exist due to perceptually impoverished interface conditions (see also [7], [36]). It may therefore be a wise approach to investigate whether improved perceptual access to the task environment can serve possibly to eliminate the need for certain cognitive demands, prior to simply accepting these demands as necessary for performance and designing aids to assist the operators in satisfying them. This strategy aimed at reducing, rather than aiding, cognitive demands might offer an effective alternative to the use of intelligent decision aids in some situations. The introduction of such aids has the potential to create its own set of human–machine interaction problems. For example, operators may be no better at evaluating the correctness of machine-provided solutions than in creating solutions themselves [59].

Advances in display technology may yield methods for providing human operators with virtual environments consisting of perceptually rich information displays. This technology may soon make feasible the creation of task representations that exploit the power of human perception-action mechanisms and thereby reduce the demand for cognitively-intensive activities. Although the present research has painted a generally optimistic picture of the perceptually intensive processes that underlie skilled interaction, we must point out that very little is known about the tradeoffs that occur when a cognitively intensive task is changed into a predominantly perceptual task through the use of information-rich task representations. For example, cognitive “biases” may be traded for the limitations of perception, and we may reduce the frequency of errors resulting from highly flexible cognitive activities (i.e., “mistakes”) only to find we have increased the potential for errors resulting from less flexible perception-action mechanisms (i.e., “slips”) [34], [35]. It is certainly premature to advocate a comprehensive interface design framework until more is known about such tradeoffs.

These psychological issues, crucial to the successful deployment of new interface technologies, must be investigated via empirical methods in which the environment is systematically manipulated in order to identify regularities in human–environment interaction. The ability to make such manipulations and describe such regularities will require a psychological theory in which both the internal and external constraints upon behavior are represented in equally explicit and formal models. It is hoped that the present research, in which behavior was described using a model containing explicit human and environmental components, stimulates interest in constructing such integrated psychological accounts of interaction. A better understanding of the intimate relationship between the human and environment during the course of skilled activity is needed to ensure that the interface between these two system components will be effectively designed.

ACKNOWLEDGMENT

The authors wish to thank B. Plamondon and L. Lytton for their contributions to this research program. E. J. Hartzell was the project monitor. The authors thank S. Casner, K. R. Hammond, N. Moray, D. A. Norman, P. Piroli, and K. J. Vicente for helpful discussions on issues presented in this paper and three anonymous reviewers whose comments improved the presentation of this research.

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