SELECTED RESEARCH PUBLICATIONS IN COGNITIVE SCIENCE
BY RAND STAFF: 1979-1980

S. Goldin, B. Hayes-Roth, F. Hayes-Roth, P. Klahr,
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p. 6, Number 122.,
first line (title)
Change syntaxy to imagery. Title should read Understanding mental imagery (not Understanding mental syntaxy).
The bibliography presented on the following pages is a compilation of recent publications by some of the Rand researchers in the Information Processing Systems research program. The bibliography is selective, comprising only those papers concerned with the broad range of topics in Cognitive Science. These topics include the modeling of complex human behaviors, the construction of intelligent computer systems, and the representation of knowledge in human and computer memories. The research draws upon the disciplines of cognitive psychology, educational psychology, computer science, artificial intelligence, and linguistics.

The bibliography is organized into two sections. The first section contains abstracts for papers published between April 1979 and December 1980. The second section contains a list of titles published prior to April 1979. Rand Papers P-5950 and P-5950/1 contain abstracts for these earlier papers.

The titles are organized alphabetically, with an author index following the list of publications. The Rand researchers represented in this bibliography are Sarah Goldin, Barbara Hayes-Roth, Frederick Hayes-Roth, Philip Klahr, Dave McArthur, Cathleen Stasz, Perry Thorndyke, Don Waterman, Clairice Veit, Keith Wescourt, and Robert Wesson. Requests for reprints of Rand publications may be addressed to the Rand Publications Department, 1700 Main Street, Santa Monica, California 90406. Requests for reprints of journal articles or book chapters should be addressed directly to the author.

The Hearsay-II system, developed during the DARPA-sponsored five-year speech-understanding research program, represents both a specific solution to the speech-understanding problem and a general framework for coordinating independent processes to achieve cooperative problem-solving behavior. Discussed in this paper are the characteristics of the speech problem in particular, the special kinds of problem-solving uncertainty in that domain, the structure of the Hearsay-II system developed to cope with that uncertainty, and the relationship between Hearsay-II's structure and those of other speech-understanding systems. The paper is intended for the general computer science audience and presupposes no speech or artificial intelligence background.


The authors present a new approach to the design of large-scale simulators. Techniques developed in the area of Artificial Intelligence, particularly in the development of "expert systems," are relevant to the design of simulators that model decision-making behavior. They have adapted and extended these techniques in ROSS, a Rule-Oriented Simulation System that simulates air penetration battles.


This report describes the design and implementation of the Exemplary Programming (EP) system that allows software to be created by example. The EP paradigm is as follows: The user performs some interactive task on a computer. The EP system watches over the user's shoulder, recording the interaction between the user and the system he is using. When the task is done, EP constructs an algorithm or high-level model of the interaction. Part of this construction may involve questions to the user or advice from the user. EP constructs a program (agent) from the
model and stores it in a library for subsequent use. A critique and suggestions for the next version of the EP system are included.


This paper reports the proceedings of the Rand Workshop on Team Performance sponsored by the Office of Naval Research. This workshop considered options for future research on teams from the perspectives of a number of different disciplines. Experts in the domains of gaming and simulation, organizational theory, small group processes, cognitive psychology, training and instruction, decision theory, heuristic modeling and human engineering presented views on potential contributions of their disciplines to team research. Discussions among workshop participants focused on a range of issues, including current problems in the performance of Navy teams, the desirability of studying teams in their operational environments, the need for specifying training objectives prior to instructional design, and the need for designing team research programs prior to establishing a dedicated team research facility. A number of broad areas seems to offer promise for future research: team performance requirements, team structure, team communications, training techniques, and organizational determinants of team performance.


Human planners show a strong tendency to underestimate the time required for planned tasks. In addition, time stress increases this tendency. The more difficult it is to accomplish all tasks under consideration in the available time, the stronger the tendency to underestimate time requirements. In addition to documenting these effects, this Note provides evidence for two underlying factors. A cognitive factor refers to people's tendency to plan at high levels of abstraction. Because they fail to enumerate all time-consuming components of planned tasks, they systematically underestimate the time required to perform the tasks as wholes. A motivational factor refers to people's desire to accomplish all or most of the tasks under consideration. This motivation biases them to underestimate required times. The Note concludes with a discussion of methods for correcting underestimation of time requirements during planning.
Executive strategies determine the allocation of cognitive resources during problem-solving. Earlier research has suggested that people can adopt alternative strategies for solving particular problems. This paper examines an "opportunistic" model of executive strategies and evaluates some of its predictions for performance of an errand-planning task. Five experiments confirmed that (a) people can adopt different strategies for this task; (b) people can learn new strategies from explicit instruction or from experience; (c) problem characteristics can influence which strategy people adopt; and (d) adopted strategy interacts with problem characteristics to determine planning time and number and importance of planned errands. The results also suggested that some people have a proclivity to adopt a particular strategy and resist adopting a new one. Implications of the results and desirable properties of the model are discussed.

Situation assessment and planning rely heavily on the decisionmaker's ability to project future conditions in the environment and the impact of tentative planned actions on those conditions. This Note presents a cognitive analysis of the future projection process. It identifies three projection strategies--retrieval from experience, formal analysis, and mental simulation--and characterizes their strengths and weaknesses. It also discusses the impact of three general cognitive factors--operation at different levels of abstraction, motivational factors, and attribution problems--on the future projection process. Based on this analysis, the Note proposes a cognitive technology for developing and training effective future projection processes.

This Report summarizes a three-year research project investigating the cognitive processes underlying human planning behavior. The project focused on problems analogous to the naval tactical planning problem: How should the decisionmaker move force units from their current locations to particular task force objectives? Major project tasks included: developing a cognitive model of the planning process, implementing the model as a
computer simulation and evaluating its performance, conducting empirical research to test the basic assumptions of the model and to identify important task and individual difference factors that impact on the planning process. Based on the results of these research efforts, the project produced a preliminary set of guidelines for improving the selection and training of planners and for designing effective planning aids.


This Note reports an initial investigation of individual differences in planning. The research reported here focuses on the analysis of thinking-aloud protocols produced by five subjects as they performed a set of errand-planning tasks. The protocols were coded into content categories suggested by the opportunistic planning model developed by Hayes-Roth and Hayes-Roth (1979). Final plans were evaluated against a set of normative criteria, such as route efficiency and temporal realism. Then the occurrence of various content categories in the protocols was related to individual subjects' planning scores in an effort to describe patterns of category usage that correlated with planning skill.

This analysis highlighted a number of differences between good and poor planners. Good planners used the available set of decision categories more extensively than poor planners. In particular, good planners made more decisions establishing criteria for plan generation and evaluation, more decisions controlling allocation of cognitive resources during planning, and more decisions assessing data relevant to planned actions. Good planners also made more decisions at higher levels of abstraction, especially decisions concerning the intended outcomes of the plan and decisions concerning an overall temporal-spatial design for the plan.

Good planners also differed from poor planners in the detailed content of their decisions. They more frequently reviewed and evaluated previous decisions. They were more likely to compare alternative plan actions. They were more sensitive to constraints on when certain errands could be done and to the existence of spatial clusters of errands. They had larger repertoires of decision types governing general plan characteristics. They generated a greater number and variety of decisions determining the focus of attention. Finally, although good planners and poor planners used essentially the same criteria for generating and evaluating their plans, good planners used most of these criteria more frequently than did poor planners.
This paper presents a cognitive model of the planning process. The model generalizes the theoretical architecture of the Hearsay-II system. Thus, it assumes that planning comprises the activities of a variety of cognitive "specialists." Each specialist can suggest certain kinds of decisions for incorporation into the plan in progress. These include decisions about: (a) how to approach the planning problem; (b) what knowledge bears on the problem; (c) what kinds of actions to try to plan; (d) what specific actions to plan; and (e) how to allocate cognitive resources during planning. Within each of these categories, different specialists suggest decisions at different levels of abstraction. The activities of the various specialists are not coordinated in any systematic way. Instead, the specialists operate opportunistically, suggesting decisions whenever promising opportunities arise. The paper presents a detailed account of the model and illustrates its assumptions with a "thinking aloud" protocol. It also describes the performance of a computer simulation of the model. The paper contrasts the proposed model with successive refinement models and attempts to resolve apparent differences between the two points of view.

Planning requires an individual to make a series of decisions about an intended course of action. This paper evaluates two major assumptions of an "opportunistic" model of the planning process: (a) that planners make decisions at different levels of abstraction; (b) that prior decisions constrain the choice of subsequent decisions; and (c) that planners generate decision sequences opportunistically. The results of three experiments supported these assumptions. In Experiment 1, subjects' sortings of statements representing different planning decisions confirmed the postulated levels of abstraction. In Experiment 2, particular prior decisions influenced subjects' choice between alternative subsequent decisions. In Experiment 3, different prior decisions influenced subjects to choose subsequent decisions at either higher or lower levels of abstraction.

In a recent article, Anderson argued that behavioral data could
not distinguish alternative theories of memory representations. The theorem Anderson proved does not support his conclusions.

Five fallacies in his argument are criticized: (a) Behavioral data cannot distinguish alternative models; (b) an invertible function relates corresponding states of alternative representation theories; (c) propositional models can account for data supporting image models and thus, warrant equal credibility; (d) propositional descriptions constitute parsimonious models; and (e) unless explicitly operationalized, image models cannot support theoretical or empirical research. Contrary to these beliefs, representational differences can qualitatively affect performance, and such important differences apparently characterize the analog class of imagery models.


A briefing presented at the Symposium on Artificial Intelligence in Information Science during the 1979 Annual Meeting of the American Society for Information Science (ASIS) in Minneapolis. Discusses the creation of a knowledge system and problems relating to it. Twenty examples are illustrated and discussed providing details on knowledge systems and data representation. Topics include: matching and abstraction in knowledge systems, knowledge bases, information retrieval, partial matches, and future research issues.


This paper considers knowledge acquisition and skill development as an iterative process. In the first phase, an initial capability is achieved by understanding instructions and following advice. Once a person (or machine) tries out its new knowledge, a variety of potential problems and learning opportunities arise. These stimulate refinements to previous knowledge which, in turn, reinitiate the entire cycle. This learning paradigm has led to new work in knowledge representation, operationalization, expectation-driven bug detection, and knowledge refinement.
techniques. This paper explains how advice is converted into operational behavior, how unexpected or undesirable behavioral outcomes stimulate learning efforts, and how the bugs responsible can be diagnosed and repaired. These phenomena are illustrated with examples of human and machine skill development in a familiar card game. The proposed learning methods provide a basis for a deeper understanding of skilled behavior and its development than previously possible.


Principal findings and recommendations of a two-year study of machine-aided knowledge acquisition. The report discusses the transfer of expertise from humans to machines, as well as the functions of planning, debugging, knowledge refinement, and autonomous machine learning. The research method emphasizes iterative refinement of knowledge in response to actual experience. A machine's "knowledge" is acquired from a human, who provides concepts, constraints, and problem-solving heuristics to define some minimal level of performance. Semi-automatic methods convert the initial knowledge into a working program whose resulting behaviors can be used to diagnose problems and design refinements. Methods formulated here may reduce or eliminate much of the human involvement currently required in this process. The approach is illustrated by application of the paradigm to the game of hearts. Recommendations suggest increased emphasis on core research problems standing between current technology and the capability of automatic knowledge programming and refinement.

125. Klahr, P. Conditional answers in question-answering systems. Proceedings of the Sixth International Joint Conference on Artificial Intelligence, Tokyo, Japan, 1979, 481-483.

In many cases a deductive question-answering system cannot find complete proofs to answer questions requiring deductive support. In some cases information needed to complete proofs is missing from the knowledge base. In other cases processing limits may have been reached before proofs could be completed. Rather than disregarding such partial proofs as most systems do, the DADM system displays them to users and identifies subproblems that remain unresolved. Answers emanating from partial proofs include remaining subproblems as "conditions" which must be true for the answers to be valid.

Knowledge engineering has been successfully applied in many domains to create knowledge-based "expert" systems. We have applied this technology to the area of large-scale simulation and have implemented ROSS, a Rule-Oriented Simulation System, that simulates military air battles. Alternative decision-making behaviors have been extracted from experts and encoded as object-oriented rules. Browsing of the knowledge and explanation of events occur at various levels of abstraction.


Large-scale simulators have been plagued with problems of intelligibility, modifiability, credibility and performance. Techniques developed in the area of Artificial Intelligence, particularly in the development of knowledge-based "expert" systems, are relevant to the design of simulators that model decision-making behaviors. We outline the problems we have encountered in large-scale simulation and present an approach that incorporates and extends those techniques. We describe ROSS, a Rule-Oriented Simulation System, that embodies these techniques in the domain of military air battles.


This paper describes a deductive processor designed to enhance the capabilities of the CONVERSE natural-language question-answering system. The emphasis is on deduction within a question-answering context rather than within a mathematical inference system. The deductive processor has been designed to find, for a given input question, the relevant general premises needed for deducing an answer. Selecting relevant premises is most crucial when there exists a very large number of premises, most of which are irrelevant to any particular query. The deductive system first constructs preliminary, skeletal derivation proposals. The purpose of these proposals is to find possible deductions before any attempt is made to verify the proposals. Verification is thus delayed until global proof plans have been established. Later processing phases examine the variable flows (substitutions) within a proposal to detect possible collisions and search the fact file for compatible sets of
values for instantiations. The use of semantic information is incorporated into the system.


Intelligent systems can explore only tiny subsets of their potential external and conceptual worlds. To increase their effective capacities, they must develop efficient forms of representation, access, and operation. In this Note we develop several techniques which do not sacrifice expressibility, yet enable programs to (semi-)automatically improve themselves and thus increase their productivity. The basic source of power is the ability to predict the way that the program will be used in the future, and to tailor the program to expedite such uses. Abstraction, caching, and expectation-simplified processing are principal examples of such techniques. We discuss the use of these and other economic principles for modern AI systems. Our analysis leads to some counterintuitive ideas and proposed policies which are not generally followed because their contribution to overall cognitive utility is not readily apparent. For example, we challenge the typical practice of storing properties "economically" in hierarchical inheritance nets. That nonredundant storage practice provides some storage cost savings, but significantly increases processing costs. As an alternative, we suggest storage schemes to improve performance by exploiting various forms of redundancy consistent with general caching heuristics.


This paper describes the influence of individual differences in abilities and subject-selected techniques for learning maps. Verbal protocols were obtained from 25 subjects who differed in psychometrically measured spatial restructuring and visual memory abilities. These protocols suggested a number of learning procedures and strategies that subjects used to focus attention, encode information and evaluate their learning progress while studying a map. High ability subjects differed from low ability subjects in the overall strategies they adopted to approach the learning problem, in their use of imagery for encoding spatial information, and in their subsequent recall of spatial attributes of the map.


This study investigated two sources of individual differences in map learning: abilities and learning procedures. Twenty-five subjects provided verbal protocols while learning two maps. Visual-spatial ability was highly correlated with recall of spatial attributes of the map and with overall performance, while associative memory ability was most correlated with verbal attribute recall. Successful learners more frequently employed procedures for encoding spatial information and assessing learning progress. However, high and low ability subjects differed little in the study procedures they chose. Although both ability differences and procedure use were important contributors to performance, abilities were the strongest predictors of map learning. We concluded that: (1) using effective study procedures influences map learning, and (2) high ability subjects benefit more from using these procedures than low ability subjects.


Four experiments investigated map clutter as a source of distortion in subjects' estimates of distance. In Experiments 1 and 2, subjects estimated distances between pairs of points on a
memorized map. In Experiment 1, they learned relative distances among cities incidentally; in Experiment 2, they learned these distances intentionally. In both experiments, estimates increased as a linear function of the number of intervening points along the judged path. In Experiment 3, subjects estimated distances while viewing the map. With this procedure, the effect of clutter was reduced but not eliminated. In Experiment 4, the clutter effect was demonstrated using subjects' pre-experimental knowledge of U.S. geography. Psychophysical power functions relating true to estimated distance provided a good fit to both memory and perception data. These results suggest an analogy between perceptual and memorial processes of distance estimation. The estimation model providing the best fit to the data assumed that subjects perceptually scan a route (or a mental image of a route) from the starting point to the destination point and use scan duration to determine route distance.


Summarizes a three-year investigation of the knowledge and processes people use to learn and make spatial judgments in large-scale environments. Experiments in map learning indicated that both the use of effective study procedures and visual memory ability determine success at learning a map. All but low-ability people benefit from training in effective study procedures. Studies of people's procedures for accuracy at estimating distances on maps indicated that map clutter increases subjective distance between two points. A third series of studies investigated differences in the knowledge people acquire from navigation and from map learning. Studying a map leads to a global representation of the environment, while navigation provides a linear, or procedural representation. Navigation experience is optimal for estimating route distances and orienting oneself toward unseen locations. Map learning is optimal for estimating the shortest distance between two points and determining relative locations of objects.


This Note proposes models of the spatial knowledge people
acquire from maps and navigation and the procedures required for spatial judgments using this knowledge. From a map, people acquire survey knowledge encoding global spatial relations. This knowledge resides in memory in images that can be scanned and measured like a physical map. From navigation, people acquire procedural knowledge of the routes connecting diverse locations. People combine mental simulation of travel through the environment and informal algebra to compute spatial judgments. An experiment in which subjects learned an environment from navigation or from a map evaluates predictions of these models. With moderate exposure, map learning is superior for judgments of relative location and straight-line distances among objects. Learning from navigation is superior for orienting oneself with respect to unseen objects and estimating route distances. With extensive exposure, the performance superiority of maps over navigation vanishes. These and other results are consonant with the proposed mechanisms.


Decisionmakers must frequently assimilate a large number of facts from several documents, organize related facts in memory, and reason using the acquired knowledge. Nine experiments investigated how people learn and retain knowledge in texts and perform inferential reasoning (using several facts to generate or verify conclusions). Individual experiments examined the influence of text structure, the learnability of individual facts, the acquisition of new knowledge conforming to a previously learned structure, the integration of related but separately learned facts in memory, search and verification processes for inferential reasoning, and techniques for improving the organization of information in memory. Results are presented in the context of models for knowledge representation and processing. A set of principles for improving human learning are derived, including text formats that facilitate knowledge acquisition and integration.


This study investigated the procedures subjects use to acquire knowledge from maps. In Experiment 1, three experienced and five novice map users provided verbal protocols while attempting to learn a map. The protocols suggested four categories of processes that subjects invoked during learning: attention, encoding, evaluation, and control. Good learners differed from
poor learners primarily in their techniques for and success at encoding spatial information, their ability to accurately evaluate their learning progress, and their ability to focus attention on unlearned information. An analysis of the performance of experienced map users suggested that learning depended on particular procedures and not on familiarity with the task. In Experiment 2, subjects were instructed to use (a) six of the effective learning procedures from Experiment 1, (b) six procedures unrelated to learning success, or (c) their own techniques. The effective procedures set comprised three techniques for learning spatial information, two techniques for using self-generated feedback to guide subsequent study behaviors, and a procedure for partitioning the map into sections. Subjects using these procedures performed better than subjects in the other groups. In addition, subjects' visual memory ability predicted the magnitude of the performance differential.


A design for a large-scale research program on improving Navy team effectiveness. The report assesses the most critical Navy teams, identifies deficiencies in the performance of these teams, and recommends new research that could lead to significant improvements in team performance. The major conclusions are (1) teams performing time-stressed decisionmaking using symbolic information are most critical to mission effectiveness and ship survivability, (2) several currently available instructional methods could immediately improve training, (3) new interdisciplinary research should study simulated teams in laboratory task environments that provide computer-controlled task scenarios, realistic environmental and enemy models, and intra-team communications networks, and (4) promising approaches to improving teams include improving performance models of team tasks, improving the tools and methods of training, compensating for disruptive effects of turnover in team personnel, improving team organization, and improving human-machine systems to aid task performance.


This Note responds to the speculations of Rule and Curtis that two operations may underlie Veit's "ratio" and "difference" data. Rule and Curtis attempted to simulate Veit's data by the theory that judges perform two operations corresponding to task instructions. They were able to transform both differences and ratios by separate weak monotonic transformations to the same
order and scale. From this they concluded that Veit's data may have been so generated and thus her conclusion that respondents use only one operation for "ratios" and "differences" is suspect. However, reanalysis shows that the simulated data do not approximate Veit's data and that Veit's techniques would have led to a correct diagnosis of Rule and Curtis's simulated data. Other theories postulated by Rule and Curtis that experimental procedures may influence rank orders of "differences" and "ratios" so as to cancel the expected nonmonotonic relationship between the two response matrices are also discussed.


User-oriented systems for capturing expertise are discussed and illustrated within the context of RITA and ROSIE, two rule-based systems developed for building intelligent interfaces and modeling expert knowledge. RITA, the Rule-Directed Interactive Transaction Agent system is operational and is currently being applied to interface and modeling problems. ROSIE, the Rule-Oriented System for Implementing Expertise, is now under development, and is intended as a tool for model builders working in complex domains for which useful analytic models are unavailable. This note is designed to promote discussion with colleagues interested in rule-based heuristic modeling and is intended for a technical audience.


This Note describes the preliminary design of a Rule-Oriented System for Implementing Expertise (ROSIE). This system is intended as a tool for model builders seeking to apply expert knowledge to the analysis of problems and to the evaluation of solutions in complex domains, especially domains for which useful analytic models are unavailable.

This preliminary design is the result of a six-month design exercise, and formed the basis of a proposal for implementation of this software system submitted to the Information Processing Techniques Office of the Defense Advanced Research Projects Agency. This Note is being distributed to promote discussion and exchange of views with colleagues interested in rule-
directed systems for heuristic modeling. It is intended for a technical audience; basic knowledge of the architecture of rule-based systems is assumed.


This report describes the design and implementation of the Exemplary Programming (EP) system that allows software to be created by example. The EP paradigm is as follows: The user performs some interactive task on a computer. The EP system watches over the user's shoulder, recording the interaction between the user and the system he is using. When the task is done, EP constructs an algorithm or high-level model of the interaction. Part of this construction may involve questions to the user or advice from the user. EP then constructs a program (agent) from the model and stores it in a library for subsequent use. A critique and suggestions for the next version of the EP system are included.


This paper discusses the design, implementation and testing of a prototype legal decisionmaking system (LDS). This system is being implemented in ROSIE, a rule-oriented language designed to facilitate the development of large expert systems. The effect of changes in the legal system on settlement decisions are studied by modifying the rules representing formal legal doctrine and noting the effect on settlement outcomes. Our current implementation of LDS consists of approximately 90 rules representing negligence and liability laws. Given a description of a product liability case the model attempts to determine what theory of liability applies, whether or not the defendant is liable, how much the case is worth, and what an equitable value for settlement would be. Our preliminary work with LDS has demonstrated the feasibility of applying rule-based modeling techniques to the product liability area. Both the basic concepts needed to describe the domain and the rules required to represent legal doctrine and strategies can be adequately represented in a rule-based formalism such as ROSIE.

An investigation of potential organizations for automated distributed sensor networks, i.e., dispersed nodes that can pool their information to perform accurate situation assessment. Laboratory experiments using a message puzzle task indicate that an "anarchic committee" organization, in which all nodes communicate with one another, consistently outperforms the "dynamic hierarchical cone" organization, in which communication is constrained and information must be obtained only from lower-level nodes. These experiments support the contention that DSNs must emphasize cooperative problem-solving rather than problem-reduction or subgoaling. A computer-based design that minimizes redundant communications in hierarchical organizations by using model-based reasoning to form expectations that guide, limit, and reduce reporting frequency is described. Finally, a method for representing hypotheses to minimize communication requirements—the process assembly network—is suggested. This concept uses active "hypotheses processes" that are responsible for predicting their own evolution over time.


This paper comparatively evaluates several models of how people encode and retrieve information from short narrative texts. The models are distinguished by their detailed assumptions on each of four issues: (1) whether or not propositions are encoded with differential probability as a function of their importance in a narrative structure, (2) whether the representation of the text in memory is hierarchical or heterarchical, (3) whether memory retrieval depends primarily on direct access or on a top-down search process, and (4) whether or not lexical information is retained in memory. Specific assumptions are combined to form twenty alternative memory models. These models are evaluated in an experiment in which subjects attempted to learn four narrative texts. Memory for the texts was tested by both recall and recognition either immediately or after a one-hour delay. Propositional recall, but not recognition, varied as a function of importance. Further, on the recognition test subjects were able to distinguish statements that had occurred in the texts from meaning-preserving paraphrases of these statements. These data suggest that (1) subjects retain lexical information in memory, (2) narrative schemata provide a framework for encoding all text propositions, (3) these schemata are hierarchically organized, and (4) the schemata are used for top-down retrieval of information at output time.


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