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ENGINEERING PSYCHOLOGY

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CONTENTS

INTRODUCTION

Engineering psychology is the study of human behavior with the objective of improving human interaction with systems. The field is partner to at least three related disciplines, overlapping but not synonymous. *Human factors engineering* considers the role of human limits, constraints, and characteristics in system design. These may include, but are not restricted to, characteristics of the brain in processing information. Thus for example, the discipline includes anthropometry—designing to accomodate the form of the human body—or the role of muscle strength and fatigue in system design. The ultimate goal of human factors engineering, however, is to improve system design, not to

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understand human behavior. The latter of course is the primary objective of engineering psychology. In Europe *ergonomics* is nearly synonymous with human factors and has, as its name suggests, a major component related to work physiology: the response of various physiological subsystems to task and environmental influences. Finally, while the psychology of *human skilled performance* addresses issues of performance in complex tasks, it does not necessarily aim its findings toward the production of better systems.

Our review focuses on the trends in engineering psychology that have emerged since Alluisi & Morgan's (1976) comprehensive review. Four major factors have produced these trends.

First, the last 15 years have seen major advances in cognitive psychology, which are finding their way into engineering-design applications. The term cognitive engineering has been proposed to describe these applications, while DeGreen (1980) has forcefully argued that the major focus of engineering psychology research must shift from sensory-motor concerns to cognitive factors. Recently the field has seen the incorporation of cognitive concepts such as attention allocation and internal models (Pew & Baron 1978, Sheridan 1981, Rasmussen 1983) into fairly rigorous engineering models of manual and process control.

Second, the revolution in computer technology has produced exponential growth in the frequency with which humans interact with computers. This growth has spawned a concomitant increase in the application of engineering psychology to human-computer interaction.

Third, computers are becoming more capable of taking over tasks once assigned to humans. Besides forcing a rethinking of the classical "allocation of function" (Eason 1980, Hart & Sheridan 1984), the resulting automation has gradually changed the roles of human operators. In many systems, humans were once active controllers and responders, bearing a heavy physical workload. Now they are becoming instead monitors and supervisors of such complex semiautomated systems as nuclear power plants and computerized manufacturing systems. Such environments impose their greatest demands on perception and attention, with critical skills of decision making and diagnosis required when automation fails. Such a trend is reflected in two important NATO-sponsored workshops, which resulted in *Monitoring Behavior and Supervisory Control* (Sheridan & Johannsen 1976) and *Detection and Diagnosis of System Failures* (Rasmussen & Rouse 1981).

Finally, the disaster at the Three Mile Island nuclear power plant (Rubenstein & Mason 1979) has directed attention to the human factors issues in the nuclear power industry. It has also made more relevant in this country the engineering psychology research on the process control industry, which was more visible in Europe during the 1970s. This interest in monitoring, supervising, and fault diagnosis in complex, heavily automated, and slowly responding systems involves all three areas mentioned above.

SCOPE AND LIMITS OF THE REVIEW

In this review we emphasize: the cognitive aspects of engineering psychology (perception, decision making, attention), issues in human-computer interaction, process control, and automation. Owing to length limitations we must neglect other research within or close to the purview of engineering psychology. Many of these areas have been addressed in special issues of *Human Factors* or *Ergonomics*, including the effects of stressors, individual differences and selection, safety research, highway transportation (*Human Factors*, Dec. 1976), aging (*Human Factors*, Feb. 1981), the handicapped (*Human Factors*, June 1978; *Ergonomics*, Nov. 1981), research methodology (*Human Factors*, June 1977), and training (*Human Factors*, April 1978).

APPROACH

The interface between humans and machines can be addressed from two different perspectives. From the viewpoint of the human factors engineer, the *systems* perspective focuses on a system (e.g. an aircraft) or a task (e.g. debugging a computer program) as a starting point and brings to bear all the human performance data that may be relevant, no matter how diverse the mental or physical operations involved. From the viewpoint of the experimental/cognitive psychologist, the *human performance* perspective models different mental operations, stages, or processes in human performance (e.g. decision making, recognition, motor control) independently of any specific physical system.

During the last decade research efforts on both sides have sought to fuse the two approaches. Human factors engineers have focused on specific component processes, while human performance researchers have examined these component processes within the framework of real-world tasks. Our review, however, still reflects the dichotomy to some degree. We adopt as a framework Wickens's (1984) model of human information processing, in which information is first perceived (detected and recognized), decisions are made on the basis of that information (relying upon working memory if necessary), and then responses are selected and executed. All of these processes depend to some extent upon the human's limited attentional resources. In the first section of this review we consider the investigation of each of these stages and the application of research to particular systems problems. In the second half of the review we discuss research more directly from the systems framework, as both the research and the tasks involved encompass all phases of human information processing, including human-computer interaction, process control, and automation.

A number of books address problems of engineering psychology from a human information processing framework. Some emphasize the human information processing perspective (i.e. Welford 1976, Anderson 1979, Lachman et al 1979, Holding 1981); some stress the systems and human factors perspective (Bailey 1982, McCormick & Sanders 1982, Kantowitz & Sorkin 1983); and some fall in between (Sheridan & Ferrell 1974, Underwood 1978, Wickens 1984). Sheridan & Ferrell's book has a heavy mathematical flavor, while Wickens' book adopts a framework similar to that presented below for organizing research on human information processing limits and their implications for system design.

HUMAN PERFORMANCE LIMITS

Perception

DETECTION Engineering psychology research in this area has been heavily vision-oriented, with major research trends in two closely related areas: vigilance and visual search. The topic of human vigilance—why people fail to detect sometimes salient visual events after a long watch period—has been at the forefront of research during the past 20 years. While the intensity of research has declined somewhat, the subject still receives scrutiny. Methodological questions related both to dependent variables (e.g. Craig 1979, Long & Waag 1981) and to experimental artifacts (Craig 1978), as well as experimental questions regarding the detection of multiple targets (Craig 1981), redundancy of signal representation (Colquhoun 1975), and the role of working memory (Parasuraman 1979), have been investigated. Murrell (1977) has considered machine aids in vigilance, while Parasuraman's (1979) paper reflects an important new effort to account for the vigilance decrement in terms of working memory deficits. Books by Mackie (1977) and Davies & Parasuraman (1980) summarize much of the recent research in the field.

Unfortunately, much of this research has still failed to clarify how relevant the phenomena examined in the laboratory are to real-world vigilance problems. Both Ruffle-Smith (1979) and Lees & Sayers (1976) have addressed vigilance more directly from the complex perspectives of the aviation environment and the nuclear process control room, respectively. Sheridan & Johannsen's (1976) book, *Monitoring Behavior and Supervisory Control*, integrating the papers of a NATO conference, extends classic vigilance research to the general environment faced by the supervisor/monitor of the nuclear power reactor. Here an operator monitors a complex system, interacting little with it until the infrequent events occur that must be detected, diagnosed, and acted upon.

Visual search differs from vigilance by involving the important element of stimulus location within the visual field. Two contexts—that of the industrial inspector and of the Air Force pilot—have been thoroughly investigated. Excellent work on the former has been carried out by Drury and his associates [as reviewed in Drury (1982)]. In this research, fruitful models predicting the latency and accuracy of the detection of flaws in industrial products like sheet metal have been proposed, and experimental variables have been examined related to the effect of multiple targets on search performance (Morowski et al 1980), the influence of different training programs (Czaja & Drury 1981) and display aids (Liuzzo & Drury 1980), and the merits of human versus machine inspection (Drury & Sinclair 1983).

Recent research on airborne visual search also attempts to derive predictive models of the search time and accuracy of an airborne observer spotting a terrestrial or flying target. In formulating these models, researchers are recognizing the importance of such cognitive factors as expectancy and target uncertainty, as well as such physical ones as intensity and acuity (Greening 1976). The entire June 1979 issue of *Human Factors* is devoted to visual search and target acquisition. In this issue, Teichner & Mocharnuk (1979) present a valuable overview and summary of existing models.

Finally, signal detection theory remains a strong and healthy tool, applicable to a diverse array of detection problems. The theory's ever-critical distinction between sensitivity and response bias and the variables that influence each has proved useful not only to work on vigilance and search, but also to that on an air traffic controller's detection of impending collisions (Bisseret 1981), a pilot's detection of air targets (Gai & Curry 1978), polygraph lie detection (Ben-Shakhar et al 1982), eyewitness testimony in criminal proceedings (Malpass & Devine 1981), and medical detection and diagnosis (Swennsen et al 1977). Swets & Pickett (1982) offer an excellent overview of these applications of signal detection theory, with strong emphasis on the medical field.

DISPLAY CONCEPTS AND MEMORY Rapid advances in computers and display technology have made a host of new display concepts available for presenting complex information to the human operator. More research is urgently needed on how this technology can best exploit the strengths and avoid the weaknesses of human perceptual and cognitive processing. Critical reports have examined the roles of color (Christ 1975, Christ & Corso 1983), three-dimensional graphics (Getty 1982), "holistic" object-like displays (Jacob et al 1976, Goodstein 1981, Woods et al 1981, Wickens 1984), "face" displays (Jacob et al 1976), synthetic voice displays (Nakatani & O'Conner 1980, Simpson & Williams 1980, Luce et al 1983, McCauley 1984, Wickens et al 1983b, 1984), and integrated computer graphics (Goodstein 1981, Mitchell & Miller 1983).

Unfortunately, new display technologies may be implemented without theory-based empirical guidelines having been developed to indicate when they are more and less useful. Such guidelines should be based in part upon the working memory demands of the task and the integrative power of the display. For example, Wickens et al (1983b, 1984) have attempted to provide such guidelines on the appropriateness of speech displays to tasks involving a continuum of working memory operations from the spatial to the verbal. These investigators propose that verbal tasks are better served than spatial ones by speech displays. Predictive displays are most successful in decreasing the working memory demanded by the mental processes of prediction (Wickens 1984). The utility of such displays has been demonstrated in the contexts of aviation (Grunwald & Merhav 1978, Jensen 1981), air traffic control (Whitfield et al 1980), industrial scheduling (Smith & Crabtree 1975, Gibson & Liaos 1978, Liaos 1978, Mitchell & Miller 1983), and process control (West & Clark 1974, Sheridan 1981).

Two additional areas of engineering psychology research have integrated perceptual and memory processes:

1. Several investigators have compared the efficacy of verbal instructions with that of pictures and flowcharts in instruction (e.g. Booher 1975, Kamman 1975, Krohn 1983), and in assisting computer programming or fault diagnosis tasks (Ramsey et al 1978, Brooke & Duncan 1980a,b; see the section below on Human-Computer Interaction). A redundant combination of both formats consistently provides more effective performance than either alone. Fitter & Green (1979) offer an excellent discussion of the use of pictures and diagrams in computer systems. They argue for the benefits of redundancy and discuss what makes graphics and flowcharts effective supplements to printed instructions.

2. A recent interest has developed in the role of *spatial cognition* in constructing maps and other navigational aids. Relevant here is fundamental research in the human factors of map layout (e.g. Potash, 1977, Noyes 1980) and the optimal format for conveying geographical information to suit specific tasks. Is it better to use maps or verbal "route lists" (Bartram 1980), or to use map study or navigation through an area (simulated or actual) to learn its geographical features (Goldin & Thorndyke 1982, Thorndyke & Hayes-Roth 1982)? What distortions of spatial cognition are imposed by the limitations of human memory, and how do they affect the performance of geographical/navigational tasks (Howard & Kerst 1981, Tversky 1981)? Thorndyke's research addresses these questions within the framework of a three-phase model describing the acquisition of geographical knowledge (Thorndyke & Hayes-Roth 1982). First, *landmark knowledge* (visual images of major landmarks) is attained. *Route-knowledge* is developed next, enabling navigation from place to place. Finally, at the most abstract level, *survey knowledge* typifies the true "cognitive" map of an area.

Response Process

Two research areas relevant to the selection and execution of responses are currently important: voice control and models of manual control.

VOICE CONTROL Advances in speech recognition technology have made feasible voice control of, or voice interaction with, inanimate systems. Lea (1980) offers a good overview of issues in this area, and McCauley (1984), along with several papers in the 1982 and 1983 *Proceedings of the Human Factors Society Annual Meeting*, describes guidelines for task interfacing with speech control. The use of speech control in severe environments has also been discussed (National Research Council 1984). Speech control can improve performance in environments when the hands are already busy with other tasks (Wickens 1980, Wickens et al 1983b), but beyond this no strong guidelines are available to indicate which tasks are best and worst suited to voice control. Wickens et al (1983b, 1984) have found that inherently verbal tasks are better suited for voice control. Ballantine (1980) discusses the use of voice channels in human–computer interactions, while Gould & Boies (1978) compare the advantages of voice and writing as means of creating text.

MANUAL CONTROL AND AVIATION The study of manual control and tracking has always been a cornerstone of engineering psychology, and the last decade has seen a continuation of interest in how people control aircraft, automobiles, and ships. Poulton's (1974) book summarizes much of the prior research in this area, while various volumes of the NASA-sponsored *Annual Conference on Manual Control* provide current compendia of research papers. Basic laboratory research in manual control has evolved from an interest in the human as an error nullifying compensatory tracker, to a consideration of the "four Ps": pursuit, prediction, preview, and precognition. Thus, recent investigations have examined *predictive* displays (Grunwald & Merhav 1978, Jensen 1981); *preview* and *precognitive* tracking, in which the human can either see ahead of time or has stored in memory the course to be tracked (Pew 1974, Kleinman et al 1980, McRuer 1980, Hess 1981b); and *pursuit* tracking, where the target can be pursued directly in an "open-loop" rather than a compensatorily error-correcting fashion (Hess 1981b). The differences between compensatory, pursuit, and predictive tracking in the context of aviation displays are coherently addressed by Roscoe et al (1981).

Manual control research continues to focus on modeling. McRuer (1980) surveys and contrasts two of the most successful approaches: (*a*) the classical "crossover" model, based upon linear feedback control theory (Wickens & Gopher 1977), and (*b*) the more recently developed "optimal control" model, which is both more mathematical than the crossover model and more attuned to human cognitive processes and limitations (see Pew & Baron 1978 for an intuitive overview of this model). A series of articles in the special August and October 1977 issues of *Human Factors* describe the use of these models to predict control performance and guide display design in aviation, automobile driving, target acquisition, and ship control. Intensive modeling efforts have been devoted to the first two areas. A series of studies (e.g. McRuer et al 1975, Donges 1978, Reid et al 1981b) have modeled the automobile driving process. Meanwhile, the optimal control model has been applied by Hess (1981a) to the design of flight director displays, by Baron & Levison (1975) to the design of flight attitude displays, by Stengel & Broussard (1978) to predict aircraft handling qualities and stability problems, and by Bergman (1976) and Merhav & Ben Ya'acov (1976) to design more effective flight controls.

Manual control is not the only component of the processing demands made on the pilot. A number of investigators have called attention to the more decisional/cognitive characteristics of aviation. Johannsen & Rouse (1979) offer a framework for developing more complex models of the control, planning, and decisional processes, while Govinderaj & Rouse (1981) model the time-sharing between discrete and continuous aviation tasks typical of air transport carriers. Johannsen & Rouse (1983) address the critical issue of *planning* in aviation, and Jensen (1982) reviews the literature on pilot judgment and decision making. Finally, we note five interesting and integrative treatments of human performance in aviation: Roscoe's (1981) textbook on aviation psychology, Hurst's (1976) fascinating book on *Pilot Error*, Wiener & Curry's (1980) critical discussion of flight deck automation, the October and December 1980 special issues of *Human Factors*, devoted to research and analysis of air traffic control, and the December 1984 special issue of *Human Factors*, devoted to aviation psychology. All five of these do a good job of integrating analysis of task demands with experimental research on the basic limits of human performance.

Attention

The properties and limits of human attention have been examined and applied to system design questions with increasing frequency in recent years. Designers have begun to realize that many systems impose more monitoring and processing demands on the operator than his attentional resources can meet. The recent volume edited by Parasuraman & Davies (1984) offers an excellent perspective on the current status of attention research and theory, while Wickens's (1984) two chapters on the topic specify four areas where attention research has been applied: selective attention, task configuration, individual differences, and workload.

SELECTIVE ATTENTION Engineers are currently interested in models of the attention selection process. How does the operator choose which of a vast array of instruments or tasks to observe or perform at a given time? A good portion of Sheridan & Johannsen's (1976) book is devoted to this question, and Moray presents highly readable discussions of the issues both in general (1979) and in the context of the process control environment (1981).

More specific quantitative models of the attention allocation process have been developed by Walden & Rouse (1978) based on cueing theory, by Tulga & Sheridan (1980) based upon dynamic programming, and by Pattipati et al (1982) based upon the optimal control model. These efforts examine performance in terms of how humans depart from optimal attention control. Research on the limits of selective attention has been applied to analysis of the processing of information in television ads (Warshaw 1978), to the perception of important and irrelevant details by eyewitnesses viewing crimes (Wells & Leippe 1981), and to the detection of objects outside the cockpit through "heads-up" aviation displays (Fischer et al 1980).

ATTENTION AND TASK CONFIGURATION In 1979 Navon & Gopher proposed that humans have several types of attention—they referred to these as multiple resources—and that tasks requiring different resources are more efficiently time-shared than tasks imposing their demands on the same resource. Wickens and his colleagues (Wickens et al 1981, 1983b) have examined the implications of this view for configuring complex multitask environments to distribute demands across, rather than focussing demands within, resources. For example, if audition and vision employ different perceptual resources, and speech and manual control depend on different response resources, then the use of auditory displays and speech control in otherwise heavy visual-manual environments may increase operator efficacy (Hammerton 1975, McLeod 1977, Wickens 1980, Wickens et al 1981, 1983b). The distribution of demands across other dimensions defining separate resources may have a similar effect. For example, since spatial and verbal tasks may require different resources, asking an operator to perform two spatial tracking tasks will produce poorer time-sharing than the concurrent performance of a tracking with a verbal task (Wickens et al 1983b).

INDIVIDUAL DIFFERENCES AND LEARNING Why do some people perform complex tasks better than others? The difference may derive from a difference in time-sharing capability, either inherent or developed through practice and training. The search for a "general" stable time-sharing ability that differentiates people across diverse multitask situations has generally produced more failures (Jennings & Chiles 1977, Wickens et al 1981) than successes (Sverko et al 1983). On the other hand, people may differ in terms of time-sharing abilities relevant to specific dual-task environments [e.g. time-sharing of two discrete keypress tasks, or dual-axis tracking (Damos, Smist & Bittner 1983)]. Specific attentional skills assessed in "pure" laboratory environments appear to predict performance in more complex multitask environments (Fournier & Stager 1976, North & Gopher 1976, Gopher 1982). Time-sharing performance increases as people practice in a dual-task environment (Gopher & North 1977, Damos & Wickens 1980) or as expert pilots are compared with novices (Damos 1978, Crosby & Parkinson 1979). Many of these differences result from increased automaticity (decreased resourse demand) of the single-task components, in addition to the development of time-sharing skill (Damos & Wickens 1980).

WORKLOAD The metaphor of attention as a limited commodity or set of resources underlies the concept of *mental workload,* one of the most prolific research areas in the last decade. The study of mental workload has been to the 1970s and early 1980s what research on the topic of vigilance was to the 1960s. Hundreds of empirical and theoretical articles on the subject have appeared in the last ten years, and mental workload has been the main topic or at least a major issue at several recent conferences [e.g. the NATO Conference on Mental Workload (1977), the NASA/Industry Workshop on Flight Deck Automation (1980), the USAF Workshop on Flight Testing to Identify Pilot Workload and Pilot Dynamics (1983), and the First Annual Conference on Mental Workload (1984)].

The definition of mental workload remains somewhat uncertain, though there seems to be agreement on what mental workload is not: It cannot be represented as a scalar but instead is best viewed as a multidimensional construct that includes behavioral, physiological, and subjective aspects (LePlat 1978, Johannsen et al 1979, Wickens 1979, Williges & Wierwille 1979, Eggemeier 1980, Kramer et al 1983).

The equivocal nature of the concept of mental workload is perhaps best illustrated by a survey of theoretical and empirical definitions found in the literature. Mental workload has been equated with the arousal level of the operator (Wierwille 1979); defined as a person's subjective experience of cognitive effort (Sheridan 1980); measured as the time taken to perform a task (Welford 1978); and conceptualized as the demands imposed upon the limited information-processing capabilities of the human operator (Wickens 1979). Several literature reviews also illustrate the equivocal nature of the concept of mental workload. Rolfe (1971), Brown (1978) and Ogden et al (1979) review some of the applications of dual-task techniques. Reviews by Roscoe (1978) and Wierwille (1979) are concerned solely with physiological measures. Ellis (1978), Borg (1978), and Moray (1982) concentrate on subjective measures of mental workload. Chiles (1978) and Williges & Wierwille (1979) review the behavioral techniques. That so many measurement techniques are available implies a diversity of definitions.

Such measurement techniques can be classified as: primary task measures, secondary task indexes, subjective techniques, and physiological measurements.

Primary task measures equate mental workload with performance on a single task. It is assumed that increasing the difficulty of a task will decrease the operator's performance (Hurst & Rose 1978, Wierwille & Gutmann 1978, Hicks & Wierwille 1979, Wierwille & Connor 1983). The primary task measure provides high face validity as a workload metric, does not impose additional demands on the operator, and is relatively simple to apply in operational environments. Furthermore, generic categories of task variables can be tabulated and used to predict drops in primary task performance (Johannsen et al 1979). Although primary task measures provide a reliable index of performance it is difficult to say precisely how primary task difficulty influences workload. For example, two subjects may produce the same performance scores with a different investment of resources. A second shortcoming of the primary task method of workload assessment is the difficulty of generalizing or equating the workload effects across different primary tasks.

Secondary tasks The importance of the secondary task workload methodology is illustrated by the numerous critical reviews and research articles devoted to the topic (Brown 1978, Ogden et al 1979, Pew 1979, Williges & Wierwille 1979). The several variants of the secondary task method all require subjects to perform two tasks concurrently. One task is usually designated as primary, the other as secondary. Subjects are instructed to protect their performance on the primary task by allocating sufficient resources. Increases in the difficulty of the primary task are presumed to decrease performance on the secondary task from its single task level. Hence, workload or inferred resource demands of different primary tasks may be compared. The major disadvantage of the secondary task technique is its intrusion on primary task performance. Commonly used secondary tasks include active and retrospective time estimation (Hart 1975, Wierwille & Conner 1983); tracking (Jex & Clement 1979, Wickens & Kessel 1979, Burke et al 1980); memory and classification tasks (Crosby & Parkinson 1979, Logan 1979, Schiflett 1980); monitoring (Becker 1976), probe reaction time (McLeod 1978); and random digit generation (Zeitlin & Finkelman 1975, Savage et al 1978).

Recent conceptualizations of mental workload have suggested that two tasks can be time-shared successfully to the extent that they require separate types of processing resources (Kinsbourne & Hicks 1978, Freidman & Polson 1981). Wickens (1980) has proposed that resources may be represented by three dimensions: stages of processing (perceptual/cognitive and response stages), modalities of processing (auditory and visual), and codes of processing (spatial and verbal). This theoretical approach in conjunction with empirical validation has increased the predictive power of the secondary-task technique, by allowing the practitioner to choose secondary tasks that have the same resource demands as primary tasks (Wickens & Kessel 1979, Isreal et al 1980a,b).

Subjective measures Several new or modified scales have been developed for subjective rating of mental workload. Wierwille & Casali (1983) modified the Cooper-Harper scale of Aircraft Handling Quality to assess perceptual, cognitive, and communication load. Ratings based on this scale varied systematically with task difficulty in three separate experiments. Sheridan (1980) has proposed that the subjective experience of mental workload comprises three dimensions (see also Sheridan & Simpson 1979): the time stress of the task, the amount of mental effort invested in the task, and the psychological/emotional stress imposed upon the subject by the task. Reid et al (1981a) employed conjoint analysis to derive a scale based on these three dimensions. Subjects were able to rate tasks along the three dimensions. At present, however, both the independence of the dimensions and the percentage of variance in the subjective experience of mental workload accounted for by the scale appear uncertain (Boyd 1983). A theoretically based approach to the assessment of the subjective aspects of mental workload has also been proposed (Derrick 1983). Subjects performed four tasks, singly and in all four pairwise combinations. The tasks were selected on the basis of their resource requirements, as suggested by multiple resource theory (Wickens 1980, 1984). A multidimensional scaling analysis of the subjective data produced three dimensions. The dimensions presumed to underlie the subjective difficulty ratings related to the competition for resources of the dual-task pairs, the adequacy of feedback, and a measure of heart-rate variability that appears to index the total resource demands. Recent innovations in the methodology of subjective workload assessment have produced potentially useful measurement devices. However, these scales require further validation in terms of their correspondence to other methods of workload assessment (Wickens & Yeh 1983).

Physiological techniques The major advantage of physiological workload assessment techniques is their relative lack of intrusion on primary-task performance. Since excellent reviews of these techniques are available, only a few are discussed here (Roscoe 1978, Wierwille 1979). Physiological workload assessment techniques are of two types: those sensitive to overall workload, and those reflecting one aspect of mental workload. Pupil diameter correlates highly with many different cognitive tasks (Beatty 1982). Similarly, heart-rate variability is systematically influenced by various task manipulations (Mulder & Mulder 1981, Sharit & Salvendy 1982). The P300 component of the event-related brain potential appears to index the perceptual/cognitive processing demands of a task while being relatively insensitive to the manipulation of response load (Isreal et al 1980a,b, Natani & Gomer 1981, Donchin et al 1982, Kramer et al 1983). Furthermore, the P300 can provide a measure of the resource trade-offs between two concurrently performed tasks (Wickens et al 1983a). Although physiological measures provide a continuous and relatively unobtrusive measure of workload, their cost and artifact problems preclude their use in some operational settings. These technological disadvantages should be solved in the near future.

Strategies and dissociation Research in the workload area is beginning to investigate what happens when workload measures *dissociate* (Wickens & Yeh 1983)—e.g. when two tasks are compared and one produces both better primary task performance and higher ratings of subjective difficulty. Examples such as these of lack of agreement between workload measures call for a better understanding of the information processing mechanisms that "drive" different indexes (Wickens & Yeh 1983).

The investigation of the strategy changes subjects invoke to cope with high workloads has produced interesting findings in both operational and laboratory tasks. In a series of field studies Sperandio (1978) observed the performance of air traffic controllers under different workload levels. As the workload increased, air traffic controllers gradually shifted their attention to fewer and presumably more important operational objectives. Under low workload, controllers can monitor several objectives, such as collision avoidance, rate of progress of aircraft through the system, choice of the shortest flight paths for economy of time and fuel, and the preferred altitudes of pilots. Under high workload, however, controllers shift to the primary objective of collision avoidance. Welford (1978) has suggested that at least three different types of strategies may prove useful in dealing with high workloads: (*a*) perceptual coding and motor programming, (*b*) methods of search, and (*c*) balancing conflicting factors (e.g. speed and accuracy, or errors of ommission and commission). The selection and implementation of effective and economical strategies to cope with high workloads may be a useful indicator of a highly skilled operator (Bainbridge 1978, Rasmussen 1981).

Decision Making

Two major causes account for the increasing concern in the last decade with decision making in human–systems interactions. First, greater system complexity and automation require operators to integrate massive amounts of information and make decisions. Second, cognitive psychology has advanced beyond the classical view of the human as a normative decision maker (a view that dominated the 1950s and 1960s) to a consideration of how limitations on human attention and memory affect decision making, forcing humans to employ decision making *heuristics* (Tversky & Kahneman 1974, Slovic et al 1977, Einhorn & Hogarth 1981, Kahneman et al 1982). Slovic et al's (1977) review of the decision-making literature provides an overview of the contrast between these two approaches.

DECISION AIDS Classical decision theory has had its greatest impact on engineering psychology in the area of *decision aids*, which offer a methodology and framework for breaking the global decision problem down into its basic elements—what Slovic et al (1977) call the "divide and conquer" strategy. Two related applications have proven particularly fruitful in decision aiding: decision tree analysis and multiattribute utility theory. Decision tree analysis—a procedure for choosing courses of action given probablistic estimates of the state-of-the-world and utilities assigned to different outcomes—is clearly outlined in the *Handbook for Decision Analysis* (Barclay et al 1977). Steeb & Johnston (1981) offer a computer-based system to aid group decision making within this framework, while Fischoff et al (1979a) examines the cognitive processing involved in using decision trees.

In multiattribute utility theory (MAU), the choice of a course of action, or object is supposed to be facilitated by an analysis of the attributes and relative importance of all competing alternatives. The special May 1977 issue of *IEEE Transactions on Systems, Man, and Cybernetics* was devoted to decision processes. It contains several examples of the MAU approach, including Edwards's (1977) overview of the technique and the description and validation by Weisbroad et al (1977) of an adaptive decision-aiding system employing MAU that models humans' utilities for different information sources on-line. Steeb (1980) applies the same procedures to the decision-making problem facing a supervisor of remotely controlled vehicles.

Other investigations have shown the advantage of MAU over "holistic" decision making in apartment selection (Pitz et al 1980), credit application evaluation (Stillwell et al 1983), energy policy development (Keeney 1977), and government research program evaluation (Edwards 1977). A related approach focuses more directly on the appropriate methodology for assessing the utilities employed in MAU (Edwards 1977, Keeney 1977, Beach & Barnes 1983). An overview of decision-aiding procedures that may be used in information systems is presented by Sage (1981), while Wohl (1981) has discusses the role of decision aids in Air Force command and control environments.

HEURISTICS AND COGNITIVE LIMITS Tversky & Kahneman's (1974) influential article on decision-making heuristics has generated a wave of research and theory on the decision-making process from a "non-classical" perspective. Such work examines non-optimal decision making in terms of fundamental limitations on human memory and attention (Wickens 1984). Wallsten's (1980) edited volume contains good overviews of these limitations and biases in the decision-making process.

Specific information-processing limitations affect decision making in such areas as seeking out information sources (Payne 1980), properly combining base-rate frequency information with new data in diagnosis (Carroll & Siegler 1977, Fischoff et al 1979b, Edgell & Hennessey 1980, Christenssen-Szalanski & Bushyhead 1981), changing hypotheses on the basis of new data (Arkes et al 1981, Einhorn & Hogarth 1981, 1982, Schustack & Sternberg 1981), generating diagnostic hypotheses to test (Gettys & Fisher 1978, Rasmussen 1981, Mehle 1982), integrating information concerning data reliability with the data itself (Schum 1975, 1980, Lindsay et al 1981), using negative diagnostic evidence (Balla 1980, Rouse & Hunt 1984), and revising the rules for decision making on the basis of incorrect outcomes (Einhorn & Hogarth 1978, Brehmer 1981). Many of these limitations have been identified in laboratory investigations; but psychologists and decision theorists can also demonstrate their presence outside the lab in such fields as medicine, criminal justice, and equipment troubleshooting.

APPLICATIONS TO CRIMINAL JUSTICE AND FORECASTING Books by Ellison & Buckhout (1981) and Loftus (1979) comprehensively cover applications of decision theory to the legal field. Ebbeson & Konecki's (1980) chapter surveys applications of this research to judicial decisions concerning parole and sentence setting. One productive approach has examined biases in eyewitness testimony. Some of this research has focused directly on the factors that affect the initial perceptions accuracy—for example, physical conditions, number of people involved, or time of day (e.g. Tickner & Poulton 1975), whether the crime was violent or not (Clifford & Hollin 1981), or whether many irrelevant details were perceived (Wells & Leippe 1981). Other studies have examined the influence of memory distortions on later accuracy of recall (Loftus 1979, 1980, Malpass & Devine 1981), focusing on biases imposed by events occurring between the crime and the testimony (Gorenstein & Ellsworth 1980) and studying how initial accuracy can be restored (Malpass & Devine 1981).

Schum (1975, 1980) has presented a formal model for how reliability information should be integrated. Others have noted that the eyewitness's asserted confidence seems unrelated to the accuracy of recall (Leippe et al 1978, Lindsay et al 1981), a tendency that is more pronounced with violent than with nonviolent incidents (Clifford & Hollin 1981). Some studies have employed mock jurors who interrogate the eyewitness. Such jurors are relatively insensitive to discrepancies between the witness's claims to reliability and his testimony's actual accuracy (Schum 1975, Lindsay et al 1981). Loftus (1980) has found that exposure to expert testimony on the unreliability of eyewitnesses can somewhat improve jurors' sensitivity to witness bias.

The relation between confidence and accuracy has also been examined in studies of forecasting (Murphy & Winkler 1974, Fischoff & MacGregor 1981). *Overconfidence* in forecasting occurs when the probability that a forecast will turn out to be correct is considerably less than the prior expression of confidence in the forecast. Finally, Fischoff & MacGregor (1981) have examined techniques for improving forecasting, including feedback about overconfident forecasts and prescriptions to be cautious.

Causal Inference and Diagnosis in Medicine and Troubleshooting

How well do humans (*a*) predict symptoms from known causes and (*b*) diagnose causes from known symptoms? Much of the human engineering work in these areas is either basic research on human biases, research applied to medical diagnosis, or the application of knowledge to equipment troubleshooting.

Einhorn & Hogarth (1982, 1983) have integrated their research on how humans infer causality into a theory identifying the factors that induce spurious perceptions of causal relations—e.g. the contiguity of two events in time and space. The excellent collection of readings edited by Kahneman et al (1982) devotes four papers to the inference of causality. In one, Tversky & Kahneman describe a human bias toward causal rather than diagnostic inference (but see Burns & Pearl 1981). Perhaps the most integrative treatment of diagnosis in applied contexts appears in Rasmussen & Rouse's (1981) *Human Detection and Diagnosis of System Failures*, summarizing the proceedings of a 1980 conference on that topic.

Specific applications of decision theory to medical decision making have taken several forms. Signal detection theory has been used to model the detection of tumors and other abnormalities (Lusted 1976, Swennsen et al 1977). Investigators have studied the use or disuse of disease prevalence rate information in medical diagnosis (Lusted 1976, Balla 1980, Christenssen-Szalanski & Bushyhead 1981, Christenssen-Szalanski & Beach 1982), and the influence of overconfidence and poor feedback on physician's diagnostic ability (Arkes et al 1981, Brehmer 1981). Eddy (1982) addresses the influence of confusions between causal inference (probability of symptoms given a disease) and diagnostic inference (probability of disease given the symptoms) on the diagnosis and treatment of breast cancer. The book edited by Dombal & Grevy (1976) summarizes research and theory concerning medical decision making, while Fitter & Cruickshank (1983) offer explicit guidelines for the use of computers in the decision making process.

In an integrated program of research, Rouse and his colleagues (Rouse

1979a,b, Rouse & Rouse 1979, Hunt & Rouse 1981, Johnson & Rouse 1982b, Rouse & Hunt 1984) have examined the nature of human troubleshooting abilities. Experimental results have been obtained both in a generic or "context-free" network of nodes and logical operations known as *TASK* (Rouse 1979a,b,) and in simulations of more context-specific environments related to identifiable systems (Hunt & Rouse 1981, Johnson & Rouse 1982b). These investigations have explored the use of non-optimal tests and the effects of system complexity, computer aiding, and forced-pacing on the process of fault location. Findings of these studies reviewed by Rouse (1981a) and Rouse & Hunt (1984), indicate that the human is good at recognizing familiar patterns of symptoms in context-specific environments but often neglects to use evidence about healthy components to limit the possible alternatives. Troubleshooting aids that unburden memory by keeping track of test outcomes seem particularly helpful in diagnostic tasks.

How well can troubleshooting skills acquired in context-free training be transferred to context-specific environments? Rouse notes positive transfer to diagnosis of both aircraft power plant failures (Johnson & Rouse 1982b) and automotive failures (Hunt & Rouse 1981). Johnson & Rouse (1982b) demonstrate the advantage of incorporating generic troubleshooting training with conventional video instruction. Brooke & Duncan (1983) also describe generic trainers for use in troubleshooting.

Efforts have also been made to model both the troubleshooting task and the performance of the human operator. Rouse & Rouse (1979) and Wohl (1983) have attempted to model the complexity of troubleshooting problems in a manner that can predict both the time to identify failures (Wohl 1983) and the qualitative nature of tests and actions taken (Rouse 1979b). According to Wohl's data, the distribution of repair time is accurately predicted by the complexity of component interrelations. Here the upper bound to repair time seems to be predicted by the limits of human working memory (7 ± 2 chunks). Since the computer, unlike the human designer, is not constrained by these limits in conceptualizing a system, Wohl worries that "unsolvable" diagnostic problems may become more prevalent as computers design more complex circuitry.

Wohl's model takes into account Rasmussen's distinction (1981; Rasmussen & Jensen 1974) between "S-rules" and "T-rules" in troubleshooting. S-rules involve familiar patterns of symptoms that automatically trigger the appropriate fault category by a pattern recognition procedure. T-rules, used when S-rules fail, require systematic, attention-demanding applications of sequential tests. S-rules tend to be context-specific; T-rules are context-free.

Other important work in troubleshooting and diagnosis has addressed the role of familiarity and memory in diagnosing circuit wiring problems (Egan & Schwartz 1979), the role of hypothesis generation in the diagnostic process

(Gettys & Fisher 1978, Mehle 1982), the reluctance of diagnosticians to revise or change diagnostic hypotheses on the basis of contradictory data (Rasmussen 1981, Einhorn & Hogarth 1982), the limiting role of working memory in constraining the tests made in electronics troubleshooting (Rasmussen & Jensen 1974), and the incorporation of time and expected cost into a model predicting the selection of different problem-solving or troubleshooting strategies (Smith et al 1982). Bond's (1981) discussion of troubleshooting in the computer industry focuses less on human limitations as the cause of diagnostic failures and more on the avoidance of such failures by a profit-oriented industry attentive to its customers' desire for equipment easy to troubleshoot.

Errors and Internal Models in Human Performance

ERRORS Before turning to research on specific systems, a word should be said concerning the dependent variables used in human performance research. In much of this research, processing latency has been viewed as the primary dependent variable of interest. Error has been seen as a "nuisance variable" to be kept low and constant across conditions, or as a variable to be converted to percentage scores or transmitted information, as a second indicator of performance. While some recent work treats the systematic relation between error rate and latency—the so-called speed-accuracy trade-off—(see Pachella 1974 and Wickelgren 1977 for overviews), a growing number of studies examine the nature of human error per se. Rouse & Rouse (1983b) have distinguished two approaches to human error:

1. The probabilistic approach is typified by the work on human reliability analysis, applied by Swain (1977, Swain & Guttman 1980) to the nuclear power plant environment. Swain attempts to combine task-specific human error probabilities with machine error probabilities to derive measures of total system reliability. Adams (1982) has pointed out the current constraints and limitations of this potentially useful technique.

2. The second approach views errors as caused by breakdowns in the natural course of human information processing. Much of this work follows from the classic analysis of aircraft errors by Fitts & Jones (1961). An integrative overview by Norman (1981a,b) distinguished errors occurring early from those occurring late in the processing sequence and provides numerous anectdotal examples, as does Reason (1984). Roberts et al (1980) have used multidimensional clustering techniques to categorize errors of the P-3 pilot into those of judgment, oversight, and skills. Rouse & Rouse (1983a) have presented a more elaborate error classification and analysis methodology that considers errors in terms of several different stages of information processing, with different contributing causes at each stage. Johnson & Rouse (1982a) applied

this scheme to the analysis of troubleshooting errors made by maintenance trainees. McRuer et al (1981) have offered a similar information processing framework for errors in manual control tasks, while Fegetter (1982) presents a methodology for collecting and analyzing errors in aviation. More specific analysis of error data has been undertaken by Roberts et al (1980) in the task of the P-3 pilot, by Brooke & Duncan (1980a) for fault diagnosis, and by Van Es (1976) and Rabbitt (1978) in keying tasks. Both of the latter investigators point to the prevalence of errors of response selection and execution (the right intention but the wrong response) and to the efficiency with which they may be monitored and corrected, provided they are not indelibly transmitted to the system.

Beyond the obvious catastrophies that sometimes result from human error, Rouse & Rouse (1983b) propose two further reasons for interest in the topic: Understanding the nature and causes of error can lead to effective redesign of systems and can guide the training of human operators. The kinds of mistakes humans make when interacting with systems can also offer insight into the nature of the human's internal model of the system.

INTERNAL MODELS Engineering interest in the concept of an internal model is a result of the growing concern for the role of strategies and expectancies in human–machine interaction. In simple terms, an internal or mental model describes an operator's concept of how a system operates; expectancies comprise the operator's view of how it responds to control and environmental inputs. The internal-model concept has recently been addressed from a variety of perspectives in Gentner & Stevens' (1983) edited volume and forms the basis of optimal control models of manual control (Pew & Baron 1978), ship control (Veldhuyzen & Stassen 1977), tracking semipredictable environmental signals (Kleinman et al 1980), human–computer interaction (Carey 1982), operation of pocket calculators (Young 1981), and, qualitatively, process control (Rasmussen 1983). The internal-model concept can guide the design of operator training programs and improved display interfaces. Instructional programs and display interfaces should be made compatible with the internal model so that a system is perceived to respond as it is expected to respond (Roscoe 1968). The internal model has also been used to describe and model how operators control dynamic systems (Jagacinski & Miller 1978) and how they detect failures in systems dynamics (Gai & Curry 1976, Wickens & Kessel 1981).

PROCESS CONTROL

Research on the human–machine interface confronting the supervisor/monitor of complex chemical and industrial processes has increased in the last decade. Edwards and Lees's (1974) book summarizes research performed prior to 1975, and some process-control research was carried out in Europe during the early and mid 1970s. The disaster at the Three Mile Island nuclear power plant in 1979 (Rubenstein & Mason 1979) provided a major impetus for process-control research in this country. General overviews of the nature of the process controller's task and of research in the area are offered by Baum & Drury (1976), Morris (1982), Umbers (1979b), and Wickens (1984). Sheridan (1981) focuses explicitly on the nuclear power plant monitor's task; Moray (1981) examines the role of human attention in this environment; and Cuny (1979) offers a framework for task analysis. A comprehensive report by Hopkins et al (1982) summarizes the conclusions drawn by a panel of experts on priorities for human factors research in nuclear power plant supervision. Priority should be placed on the design of annunciator and alarm systems, the development of advanced display technology, and the use of color coding.

Control

The process controller's job has been described as hours of boredom punctuated by a few minutes of pure hell. This dichotomy between routine and failure mode can be used to classify research in the area. Research in the former category has examined operators' strategies in controlling and adjusting process variables in such tasks as steel pitsoaking (Liaos 1978), distillation (Patternote & Verhagen 1979), gas grid controlling (Umbers 1979a), nuclear reactor control (McLeod & McCallum 1975, Sheridan 1981), industrial scheduling (Mitchell & Miller 1983), and more "generic" simulated process plants (Brigham & Liaos 1975, Morris & Rouse 1983). Some of these studies have examined the relative use of different controlling strategies (e.g. West & Clark 1974, McLeod & McCallum 1975), while many have focused on the nature of the display interface. Predictive information is important (Shackel 1976, Liaos 1978), and computer technology should be used to derive and present integrated display information, a point considered below (Goodstein 1981).

Detection and Diagnosis

Failure detection and diagnosis in process control have received more extensive treatment. In fact, many of the chapters in Rasmussen & Rouse's (1981) book concern the process-control environment. The research in this area falls into three overlapping areas: the nature of alarm indicators, the diagnostic process, and diagnosis training.

NATURE OF ALARM INDICATORS Reducing the confusion caused when scores of auditory and visual annunciators change state following a failure is a high priority item for research in process control (Hopkins et al 1982). Since the overwhelming array of information in conventional electromechanical displays offers little diagnostic assistance, research must determine how a computer with a flexible video display can be programmed to integrate information to best serve the operator's diagnostic need. Research has addressed the use of physical variables like color (Osborne et al 1981) and composition of display elements (Benel et al, 1981), as well as cognitive factors. In what form should the computer present the system's raw physical signals in order best to meet the operator's need for information (Kiguchi & Sheridan 1979)? As one example, some investigators have advocated probabilistic displays portraying the *likelihood* that a system or component will fail (Gonzalez & Howington 1977, Moray 1981, Sheridan 1981). Goodstein (1981) and Lees (1981) have considered the role of computer support in preserving and interpreting the *sequence* in which events occur, thereby reducing the load imposed on human memory. Rasmussen & Lind (1981) recommend displays that can present information according to the *level of abstraction* of the operator's needs—that can, for example, display either physical quantitites like pressure and temperature (low level of abstraction) or more abstract ones like energy flow and cost.

THE NATURE OF THE DIAGNOSTIC PROCESS Much research in process control is related to troubleshooting, discussed above. Beyond this, however, Rasmussen's (1981, 1983) qualitative model has influenced research on complex systems. Besides stressing the importance of mental models, Rasmussen emphasizes the information needs and decision-making processes associated with three modes of behavior: *skill-based:* highly automatic, involving well-learned actions; *rule-based:* attention-demanding, but grounded in following routine procedures; and *knowledge-based:* complex, creative, and innovative. Rasmussen (1983) has integrated this trichotomy into descriptions of the process-control task, and Pew et al (1981) have used it as a framework for analysis of specific critical incidents in nuclear power plants.

The last ten years have also witnessed an interest in the methodology for obtaining data relevant to process control and diagnostic models. Given that the ratio of observable responses to unobservable cognition is low, verbal protocols provide a logical source of such data, and several studies have argued the merits (Umbers 1979a, Bainbridge 1979, 1981, LePlat & Hoc 1981) and shortcomings (Brigham & Liaos 1975, Broadbent 1977, Umbers 1981) of this technique in deriving valid models of the process-control operator.

TRAINING AND INDIVIDUAL DIFFERENCES Operator differences due to training and abilities are beyond the scope of this review. Since they are relevant to cognitive models describing operator performance, however, process-control research in this area is worth mentioning. Landeweerd (1979) has found that subjects with high verbal ability perform better at process control tasks, while those with high spatial ability excel at diagnostic tasks. Marshall et al (1981) have examined different strategies for training process controllers, while Lees & Sayers (1976) have considered the importance of embedded diagnostic training in real simulators. Research concerning the level of operator sophistication and knowledge required for effective control and diagnosis indicates that minimal instruction in plant input-output relations is insufficient to produce good diagnosticians (Brigham & Liaos 1975, Shepherd et al 1977, Landeweerd et al 1981). However, instruction on troubleshooting procedures and heuristics related to the specific process appears to be adequate. Additional instruction in the general theory of plant operations appears to do little to enhance control or diagnostic capabilities (Kragt & Landeweerd 1974, Morris & Rouse 1983).

COMPUTERS AND AUTOMATION: THE INTERFACE AND THE LOGIC

The computer explosion has exerted two profound influences on human factors during the last ten years. First, it has made computer services such as scheduling, text editing, record keeping, and entertainment available to a wider range of users. This has brought to the forefront a whole array of research and design issues concerning the interface between humans and computers. Second, because of their increased sophistication and steadily declining cost and weight, computers are replacing humans in certain interactions with complex processes.

Human-Computer Interaction

Numerous guidelines have been compiled for designers of human-computer interfaces (Engel & Granda 1975, Smith & Aucella 1982, Towstopiat 1983). Although most incorporate psychological principles where possible, many of the design principles appear to be based on intuition and experience. Validation of such guidelines in both laboratory and operational environments has been sparse and will require substantial work over the next decade. Several investigators have recommended a more systematic construction of guidelines than is generally found in the literature. We endorse this call for development of a cognitively based performance theory of the human-computer interaction enabling the derivation and empirical validation of design principles (Fitter 1979, Moran 1981a, Card et al 1983). Some existing attempts to develop and validate human performance models are described below.

The magnitude and breadth of interest in the topic of the human-computer interaction are also illustrated by reviews on subtopics such as software design and programming (Ramsey et al 1978, Atwood et al 1979, Shneiderman 1980, Curtis 1981, Sheil 1981). These examine the effects of structural and stylistic changes in programming languages on performance, as well as the use of programming aids and debugging procedures. Others have evaluated query languages for nonprofessional programmers (Ehrenreich 1981, Reisner 1981). In many cases these reviews concern primarily the advantages and disadvantages of natural and structured query languages (Harris 1983, Hill 1983).

The methods by which subjects encode and later retrieve information relevant to the operation of computer systems have generated theoretical and empirical interest (Durding et al 1977, Carroll & Thomas 1982, Jagodzinski 1983). These reviews evaluate cognitive models of information representation for efficiency in helping the user learn new computer systems and languages. Numerous investigations of data input and retrieval devices have also been reviewed (Norman & Fisher 1982, Card et al 1983, Noyes 1983). Entire journal issues have been devoted to human-computer interaction. Special issues of the *International Journal of Man-Machine Studies* have addressed problems in software psychology (April 1981) and presented selected papers from several computer conferences (May 1978). *AMC Computing Surveys* (March 1981) devoted an issue to the human-factors considerations involved in programming and design of text editors and query languages.

PROGRAMMING Weinberg's classic text, *The Psychology of Computer Programming* (1971), provided one of the first systematic treatments of the human aspects of programming. He focused attention on individual differences in programming style and abilities, procedures for motivation and training, and social influences and personality factors relevant to the programming endeavor. Although Weinberg's book provided a wealth of information on the human side of programming, the discussion was based primarily on anecdote and insight rather than experimental results. Shneiderman's more recent text, *Software Psychology: Human Factors in Computer and Information Systems* (1980), provides an update on psychological research relevant to programming and software design, focusing whenever possible on empirical investigations of programming practices. The text examines topics such as programming language features, software quality evaluation, database query and manipulation languages, and team organization and group processes.

The discovery of large individual differences in programmer productivity has prompted examination of the learning and comprehension of the computer programming process (Brooks 1977, Barfield et al 1981, Salvendy et al 1983). Estimates of the magnitude of these differences range from a factor of 5 to a factor of 90 with programmers of comparable experience. Several investigators have suggested that a programmer's comprehension might be enhanced by the construction of a mental model of the task (Mayer 1975, Carey 1982). One method for cognitively representing the programming task is the use of metaphor. Carroll & Thomas (1982) reviewed research on the development of new cognitive structures by metaphorical extension of previously learned structures and recommended employing metaphors to enhance the learning and comprehension of computer programmers. Examples of the use of conceptual models to help the programmer learn a computer system can be found in the literature (Moran 1981b, Young 1981). DuBoulay et al (1981) instructed children in the language LOGO by using a conceptual model of a computer system which consisted of memory locations, switches, and work space. Unfortunately, the investigators did not evaluate the effectiveness of their instructional technique relative to other methods. Mayer (1981) provided naive programmers with concrete models of a computer as an aid in learning Basic-like and file management languages. These models represented the structure of the computer in terms of familar objects. For example, input was represented as a ticket window, memory was depicted as an eraseable scoreboard, and output was represented as a note pad. The use of the models enhanced the learning of complex programming tasks.

Investigators have also examined the cognitive processes involved in debugging computer programs. In these studies programmers are usually required to detect and in some cases correct syntatic, structural, and semantic bugs that have been introduced into programs. Syntatic bugs are relatively easy to detect (Boies & Gould 1974). Structural and semantic bugs, however, appear difficult to detect, and detection accuracy seems to depend on the search strategy, the kind of bug, and the aids provided to the programmers (Gould & Drongowski 1974, Gould 1975, Green et al 1980). Flowcharts of program structure aid debugging in some situations, especially with complex programs (Shneiderman et al 1977, Brooke & Duncan 1980a,b).

The increase in the cost of software development and the decrease in expenses associated with computer hardware have focused attention on the prediction of programmer ability. Although several standardized tests of programming ability have been constructed, their effectiveness is uncertain (Shneiderman 1980). Other indexes of programming ability such as SAT scores and college grades in math, science, and English account for only a small proportion of variance in performance on programming tasks (Barfield et al 1981). A syntatic/semantic model of programmer behavior, which suggests that experience in programming results in an increased capacity for recognizing and abstracting program structures, has led to the construction of a memorization/reconstruction test of programmer ability (Shneiderman & Mayer 1979). The task requires programmers to memorize and later reconstruct a section of code. As predicted by the syntatic/semantic model, experienced programmers and students with high grades in computer classes are significantly better at reconstructing code than less experienced programmers and students with lower grades (Shneiderman 1977, DiPersio et al 1980). Also consistent with the model, the number of lines perfectly recalled does not vary significantly between groups of programmers (Atwood & Ramsey 1977). The generation of tests on the basis of a theoretical framework appears to offer a promising alternative to the traditionally atheoretical investigation of programming ability.

TEXT EDITORS Text editors offer an ideal medium for studying human performance characteristics and cognitive processes. The editing of a manuscript includes a variety of information processing activities from the encoding of text on a CRT, through the retrieval of information from memory and its integration with new material, to the selection and execution of data entry and modificaion commands. Embley & Nagy (1981) review recent studies of the behavioral aspects of text editing. The review outlines several theoretical models of the editing process, emphasizing the potential contribution of cognitive psychology to the design of text editors.

Card et al in their recent text, *The Psychology of Human-Computer Interaction* (1983), propose a cognitively based model of text editing. Their GOMS model describes a user's cognitive structure in terms of goals, operators, methods for achieving goals, and the selection rules for choosing among competing methods. The model has been tested with several text editors and provides a reasonable account of user performance. One interesting aspect of the model is its flexibility in analyzing editing tasks at different levels of detail. The model can predict performance from the single keystroke level to the level of a unit task. A set of user-interface design principles has been derived from the model. Robertson & Black (1983) proposed a model to represent the goals and plans of text editor users. Their model, based on goal-fate analysis (Schank & Abelson 1977), represents the relationships among a user's multiple goals and shows how errors can result from poorly conceived plans. Although the model still requires additional empirical validation, it offers a potentially useful method for examining the learning of text editors and provides information on user's text editing strategies.

The learning of text editors has also been explored by examining the analogies users employ while building a representaton of the text editing commands. Douglas & Moran (1983) argue that novices use a typewriter analogy to aid them in learning editing commands. An analysis technique is proposed and data are presented suggesting that errors can be predicted on the basis of the correspondence between typewriting and text editing commands. Other investigators have compared screen editors with line editors (Gomez et al 1983) and examined the effects of differences in screen formatting (Darnell & Neal 1983) on the learning of text editors.

DATA MANIPULATION AND RETRIEVAL The continuing increase in the number of casual users of computer systems has prompted examination of the human–computer interface (Nickerson 1981). In most cases it is not necessary for casual users to specify (using a procedural query language) the procedures by which the computer accesses the information they require but only to state (using a nonprocedural query language) the result they want the computer to accomplish. Query languages are special-purpose languages constructed to retrieve information from a database. The language is usually intended for nonprofessional programmers and consists of a set of syntatic and lexical rules by means of which the user can question the computer. What is the best structure for nonprocedural query languages? This is one of the most frequently debated issues in computer science. Query languages occupy a continuum from unrestricted natural languages with grammatical rules and vocabulary similar to English to formal computer languages with highly restricted syntaxes and vocabularies. Natural languages have their share of proponents (Harris 1983) and detractors (Hill 1983, Small & Weldon 1983). Excellent reviews of the issue can be found in the literature (Petrick 1976, Shneiderman 1980, Ehrenreich 1981). Some investigators believe that English-based natural languages are too ambiguous for correct interpretation by a computer, while others suggest that natural languages are ideal for casual computer users since the language is already learned. Other reviews describe and evaluate the advantages and disadvantages of various formal query languages (Reisner 1981).

Although the controversy over the relative merits of query languages has been focused on the endpoints of the continuum (unrestricted natural languages and formal query languages), attention appears to be shifting toward a midpoint. How, then, shall natural languages be restricted to remedy such problems as semantic ambiguity? Natural languages have been restricted both in their grammar and vocabulary and in the domains they access. Both the number of grammatical rules and the size of the vocabulary can be substantially reduced without adverse effects on user performance (Kelly & Chapanis 1977, Hendler & Michaelis 1983, Ogden & Brooks 1983). Domain-specific natural languages have been constructed to access aircraft maintenance information (PLANES: Waltz 1978), mimic a Rogerian psychotherapist (DOCTOR: Weizenbaum 1976), and provide information on a supplier-parts-project database (RENDEZVOUS: Codd 1978). Several restricted-domain natural language systems have also become commercially available (e.g. ROBOT: Harris 1977).

An alternative to the use of query languages for data access is menu selection. In menu selection, users choose among several preprogrammed alternatives to access the desired information. It has been suggested that menus are particularly useful for novices because the database structure provided by the menu reduces memory demands (Simpson 1982). Menu hierarchies are arranged on the basis of an interaction between breadth and depth. Breadth refers to the number of items on a single menu level while depth refers to the number of hierarchically arranged menus. What is the optimal combination of breadth and depth? Some investigators have suggested that intermediate levels of breadth and depth lead to optimal performance (Miller 1981), while others argue that performance accuracy is best with high levels of breadth and low levels of depth (Snowberry et al 1983). Two techniques aid novices in accessing deeply embedded menus. The availability of a pictorial representation of the menu structure appears to facilitate development of a useful mental model of the system (Billingsley 1982). Natural-language menus have also been found easy to use with deeply embedded menus, presumably because sentences provide an understandable structure (Tennant et al 1983).

The structure of information in the database has a powerful influence on user performance in data manipulation and retrieval tasks. Most databases use one of the three common data-storage models: the network model, the relational model, or the hierarchical model. Evaluations of the effects of data models on user performance have not found a clear superiority for any of these three. Lochovsky (1978) employed three separate data manipulation languages that reflected the three data models and found that novices' queries were best with the relational language. Brosey & Shneiderman (1978) discovered that novices comprehended database elements best when they used a hierarchical model. Durding et al (1977) found that the structure of the database strongly influenced how people organize data. Data represented in relational, network, or hierarchical formats on the basis of semantic relations was usually organized in those formats by the subjects. Thus, it appears that the selection of a data model should be based on the relations among the database elements.

DATA INPUT AND RETRIEVAL DEVICES The proliferation of computer-related tasks and the diversity of computer users have made it necesary to evaluate different input and retrieval devices. From the mid-1800s to the 1970s such evaluations involved primarily comparing different keyboard layouts (Noyes 1983). Although keyboards are still the most frequently employed input devices, other devices are rapidly becoming popular. The studies conducted to evaluate data input and retrieval devices are of two kinds: those primarily concerned with the performance characteristics of different devices, (Neal 1977, Butterbaugh & Rockwell 1982, Price & Cordova 1983, Whitfield et al 1983) and those involving predictive models. The former have compared various touch input devices, evaluated the relative advantages of different keyboard layouts, and investigated the response characteristics of multiple-button mice. In one such study, Goodwin (1975) compared subjects' performance with a lightpen, lightgun, and keyboard across several tasks. The lightpen and lightgun were at least twice as fast as the keyboard in the cursor-positioning tasks. Although these studies provide valuable information concerning the relative merits of different input and retrieval devices, they did not attempt to develop models from which performance could be predicted.

In a series of studies, Card and coworkers (Card et al 1978, 1983) examined text selection performance with four different devices: a mouse, a rate-controlled isometric joystick, step keys, and text keys. Performance on these devices was evaluated in terms of its correspondence to predictions derived from a Human Processor Model (Card et al 1983). This model, which incorporates a number of psychological principles, enables system designers to estimate the latencies of perceptual, cognitive, and motor activities. One principle, Fitt's Law, describes the time it takes to make a goal-oriented movement on the basis of the goal's size and distance from the subject. The positioning time for the continuous devices, the mouse and the joystick, was consistent with Fitt's Law. Knowledge of this relationship allowed investigators to estimate the maximum velocity with which a user could move a cursor across a cathode ray tube with a mouse. This information led to the redesign of a piece of hardware prior to the production of a text-editing system.

Other investigators have also successfully used models of human performance for the design and evaluation of data input devices. Gopher (1985) employed models of visual imagery in his design of a two-hand chord keyboard (Gopher & Koenig 1983). Norman & Fisher (1982) evaluated a number of keyboard layouts using computer simulation of the hand and finger movements of a skilled typist. By using predictive models of human performance, experimental and cognitive psychologists can aid the designer of human-computer interfaces.

Automation

Wickens (1984) describes three reasons why automation may be implemented: (*a*) to carry out dangerous functions (e.g. remotely manipulate radioactive material) or do things humans cannot do; (*b*) to do things humans sometimes do poorly because of high workload or boredom (e.g. diagnose failure or pilot certain aircraft); and (*c*) to supplement or augment human perception, memory, attention, or motor skill.

ROBOTICS The use of robots falls into the first two categories. Robots and remote manipulators are increasingly used in hazardous environments (undersea, around hazardous materials, in outer space) (Johnson et al 1983). They are also replacing factory workers in more mundane assembly jobs. Yet robots obviously need to be taught and supervised, and here human-factors issues become relevant. Birk & Kelley (1981) have summarized a conference workshop on human factors in robotics, emphasizing the importance of research on communications between robot and human, while Parsons & Kearsley (1982) and Salvendy (1983) have offered more general overviews of the state of robotics and human factors. Salvendy reviews both the social issues associated with the introduction of robots and the technical issues related to human performance characteristics. Others have examined specifically the human-factors problem associated with robotics in industrial assembly lines (Noro &

Okada 1983), undersea environments (Sheridan 1982), and outer space (Bejszy 1980). Several recent treatments of human factors in robotics are offered in recent volumes from the NASA Annual Conference on Manual Control. Other articles consider the partitioning of intelligence between humans and robots (Sheridan 1982), and sensory-motor feedback between human and robot (e.g. Book & Hannema 1980, Bejszy 1980).

AUTOMATION THAT ASSISTS A continuum exists from automation that assists to automation that replaces human beings. Automation assists with *predictive* tasks (see the section above on Display Concepts and Memory). Voice input unburdens the hands (Wickens et al 1983a), helps humans to converse with computers (Ballantine 1980), and enhances the creative composition process (Gould & Boies 1978). Computer graphics assist in proceeding through flight checklists (Rouse et al 1982) and in medical diagnosis (Fitter & Cruickshank 1983). Computer support augments an array of office functions (Chapanis 1979). The July/August (1982) issue of *IEEE Transactions on Systems, Man, and Cybernetics* contains a special section on displays for information management systems, which aid in information integration. Wohl (1981) has considered the use of computer aids for decision support in command and control situations. Felson (1978) has done the same for the investment decision maker. The consensus is that automation in these roles is beneficial.

AUTOMATION THAT REPLACES: PROBLEMS In some situations, computers replace people in functions that people perform adequately. This controversial aspect of automation forces a rethinking of the classic allocation of function between human and machine. An excellent analysis of such automation in commercial aviation (Wiener & Curry 1980) distinguished between automation of monitoring and of control functions on the flight deck. Hart & Sheridan (1984) considered the impact of automation on workload, while Rouse & Rouse (1983b) addressed the automation of decision making. While there is little doubt that automation is a necessity in such high-demand environments as the combat aircraft (Air Force Studies Board Committee 1982), several investigators have cautioned that analysis of the total system must be carried out before tasks are assigned to computers or humans (DeGreen 1980, Eason 1980, Hart & Sheridan 1984). Others have considered the specific costs and benefits of assigning tasks to one or the other (Air Force Studies Board Committee 1982, Wiener & Curry 1980), while Boehm-Davis et al (1983) have identified salient issues for human-factors research in flight deck automation. Two questions are foremost among these: How can decision-aiding techniques be used and information transfer between human and computer be improved? How can monitoring of automated systems be improved to help the operator deal with unforeseen situations? Finally, the summary review of the study panel on automation in combat aircraft (Air Force Studies Board Committee 1982), along with Wiener & Curry (1980) and Wickens (1984), has tried to specify the costs or dangers associated with automation. Wiener & Curry's review, in addition to several articles in the October and December 1981 special issues of *Human Factors* dealing with Air Traffic Control (see particularly Wiener 1977, Danaher 1980, Fowler 1980) offers salient examples of how automation has led to disasters or near disasters in aviation.

While much has been done to identify automation-related dangers, few systematic empirical investigations have been carried out. Ephrath & Young (1981) and Wickens & Kessel (1981) have examined the losses in failure-detection ability that may occur when the human operator is removed as an active participant from a flight-control loop, while Gai & Curry (1976) have tried to model the failure-detection process. Also, as noted in the section on process control, several investigators have dealt with the problems of automated information integration in alarm and other alerting systems (see Gonzalez & Howington 1977, Kiguchi & Sheridan 1979, and several chapters in Rasmussen & Rouse 1981).

ADAPTIVE SYSTEMS There seems to be a growing consensus that automation will be more effective and more accepted if (*a*) it functions in a manner qualitatively similar to that of the human operator (Air Force Studies Board Committee 1982; Wiener & Curry 1980, Hart & Sheridan 1984), and (*b*) the automation is flexible and adaptive. In a discussion of adaptive decision systems, Rouse & Rouse (1983b) comment that most decision aids are designed for the average person under the average circumstances, which greatly limits their flexibility. In a series of articles, Rouse describes the characteristics of good adaptive systems in the control of dynamic systems (Rouse 1981b), in decision aiding (Rouse & Rouse 1984), and in multitask situations in which certain tasks can be assigned either to the computer or to the human as a function of the operator's momentary workload (Chu & Rouse 1979; Rouse 1977).

Four critical research questions concerning such systems are beginning to be addressed:

1. *What task characteristics to adapt?* As noted above in the section on decision aids, Weisbroad et al (1977) and Madni et al (1982) have adapted information presentation in decision making, while Adelman et al (1982) have considered an adaptive Bayesian decision aid. Chu & Rouse (1979) have adapted the responsibility for performing the decision-making task by computer or human to the workload of the operator. Geiselman & Samet (1982) have adapted intelligence message format to operator preferences, while Lintern & Gopher (1978) have summarized a host of studies related to adapting difficulty variables to learner progress in adaptive training.

2. *What is the time frame for the adaptation?* Is it done on-line in real time, according to the momentary state of the operator, or off-line between time periods, according to the ability or preference of different operators (Rouse & Rouse 1983b)?

3. *What is the command for adaptation?* Does the operator overtly request automation when needed, or does the computer infer its need through covert channels of communication from humans to computer, interpreted within the framework of a computer's internal model of the human? Various possible channels of this communication that can be monitored on-line have been investigated, including control theory estimates of tracking behavior (Enstrom & Rouse 1977, Merhav & Gabay 1975, Wickens & Gopher 1977), decision choice preference (Madni et al 1982), voice quality (Levin & Lord 1975), tasks left undone (Rouse 1977), or physiological signals (Isreal et al 1980b).

4. *Who is in charge?* All-important is the issue of who is ultimately in charge, computer or human. How can we provide clear communications from computer to human regarding the current partitioning of responsibility? This question is discussed clearly in a review of adaptive systems by Steeb et al (1976).

Adaptive systems are worthy of far more research than they have received. Whether desirable or not, computer automation is inevitable. If they can be successfully implemented, adaptive systems provide the most flexible and graceful means of incorporating automation into complex systems for all concerned.

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