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ENGINEERING PSYCHOLOGY[1]

D. Gopher and R. Kimchi

Industrial Engineering and Management, Technion—Israel Institute of Technology, Haifa 32000, Israel

CONTENTS

INTRODUCTION

Our age is the computer age, and human interaction with an increasing proportion of modern systems entails either direct dialog with a computer system or the use of devices that incorporate artificial intelligence on one level or another. We resolved, however, not to include a separate section on human-computer interaction here. Instead, we concentrate on several problem

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areas, in each of which various aspects of computer technology emerge as major instigators of research and modeling of human behavior.

Contemporary work in engineering psychology is marked by a deep interest in high-level cognitive functions and knowledge compilation. Issues include processing and response activities involving encoding, organization, memory represenation, and retrieval of information. Although sometimes subtle, the emphasis on cognition is evident in each of the problem areas discussed here. It is the main scientific force driving current application efforts.

The link between engineering psychology and technology not only affects the content and priorities of research work in this field, but also strongly influences its life cycle and pace. Modern technology is highly dynamic and progresses rapidly. New problems and new perspectives on old problems emerge daily. The current estimate of the duration of a technological generation is about five years (Tadmor et al 1987). What are the implications of such rapid change for our domain? What strategies should be developed to confront new problems at their increasing rate of emergence?

It appears to us that the best strategy engineering psychology can adopt is to slow its response to specific elements of new technology and strengthen its linkage with basic theorectical research. Mathematical control theory of dynamic systems teaches us that when the rate of change of an input function exceeds the point-to-point tracking capabilities of a system, the system can best respond by (*a*) following higher-order, slow-moving patterns of change, and (*b*) introducing response lead-time by predicting future inputs. The importance of this analogy is twofold: First, it helps to clarify the need to concentrate on the development of general principles and methods rather than on specific local solutions. Systematic empirical evaluation of human performance in every technological situation is impractical in terms of time, cost, and generalization value. (Think, for example, of the host of text processing programs, or the multiplicity of car instrument panels.) Second, the analogy emphasizes the role of theoretical models in practical work. Only with such models can we generate prinicples and predict the future. If there existed only a limited set of slow-moving technologies, strict empirical approaches could suffice.

We concentrate here on three problem areas that emerge from present technology. We discuss the technological instigators, theoretical foundations, and applied research in the design of visual displays, assessment of mental workload, and training of complex skills. The first illustrates typical issues and problems encountered in the design of engineering systems. The second concerns evaluation of human ability to cope with the demands of tasks. The third involves training operators to master the skills required at a new work station.

We refer the reader to several recent publications that offer a broader and more comprehensive coverage of the field. *The Handbook of Human Factors*

(Salvendy 1987a), which includes 66 chapters written by 104 researchers in the field, is perhaps the most comprehensive recent review of applied work. It is complemented by the 45 chapters of a two-volume *Handbook of Human Perception and Performance* (Boff et al 1986). These chapters review and evaluate human performance theory in topics relevant to engineering psychology. Other recent overviews of traditional and new topics can be found in the 6th edition of Sanders & McCormick's (1987) textbook, in *Trends in Ergonomics/Human Performance II* (Eberts & Eberts 1985), and in *Human Factors Psychology* (Hancock 1987). Two recent volumes on human-computer interaction edited by Salvendy (1987b,c) summarize work in this rapidly growing area.

Also useful are the proceedings of the annual meetings of professional societies in the field: the United States Human Factors Society (1985, 1986, 1987, 1988), the International Ergonomics Association (1985, 1988), and The International IEEE Conference on Systems, Man, and Cybernetics (1986, 1987, 1988). Although less formal, proceedings provide a more recent update of present trends and better pointers to future directions. Given the applied nature of the field, and the fact that field professionals are frequently not pressed to publish regularly in scientific journals, proceedings also better represent the topics of interest.

The primary journals for the core applied work in this area are *Human Factors*, *Ergonomics*, *Applied Ergonomics*, and the *International Journal of Man-Machine Studies*.

DISPLAYING AND INTERACTING WITH COMPLEX VISUAL INFORMATION

Efficient ways of displaying information have been a major concern of engineering psychology since its early days. Although each of the previous reviews of the field made brief reference to these issues (e.g. Wickens & Kramer 1985), the last time a large section was devoted to visual displays was in Chapanis's chapter in 1963. Since then, rapid advances in computer technology, increased graphic capabilities, and new display devices have increased interest in this area while introducing new types of problems for research.

Technological Need

The increased complexity of today's dynamic systems entails the presentation of a wealth of information to the human operator. At the same time, the rapid advances in computer and display technology have increased both the capability of presenting multi-element, complex information on a single display and the freedom to select the aspect and mode of presentation. The range of tasks that involve interaction with the new types of displays has increased as well.

While the traditional tasks of detection, identification, and discrimination remain, growing number of more complex, high-level supervisory control and decision-making tasks now require complex evaluations and interpretations (Moray 1986; Sheridan 1987).

A display is a physical device designed to convey information as quickly and accurately as possible. It constitutes a representation of another physical or abstract system. Hence, two major issues are involved in the design of a display: (*a*) its ability to represent properly the world one wishes to represent, and (*b*) the physical properties of the display itself.

The physical attributes of the display designed according to psychophysical laws, are critical for the availability of the displayed information to the human opertor. Guidelines for design of displays still focus on the psychophysical qualities of the display, aiming at enhancing readability and legibility (e.g. Helander 1987). There is, however, a growing recognition of the need to consider human perceptual and cognitive processing as well (Foley & Moray 1987; Wickens 1987). Indeed, the human engineering literature of the last five years shows increasing interest in representational and information-processing issues, which brings this discipline closer to central questions in cognitive psychology.

Theoretical Foundation

High-powered computer graphics present a display's designer with many choices about how to present information. In order to exploit this freedom in the best possible way, we need principles of representation design.

Modern cognitive psychology is dominated by the information-processing approach (e.g. Palmer & Kimchi 1986), an attempt to specify the nature of mental representations and the processes that operate upon them (e.g. Palmer & Kimchi 1986; Chase 1986; Treisman 1986). Excellent reviews and analyses of representational systems are provided by Palmer (1978) and Rumelhart & Norman (1988). The problem of representation is one of determining a mapping between the concepts and relations of the represented world and the concepts and relations of the representing world. The distinction between analogical and symbolic (propositional) representations and the distinction between continuous and discrete representations are discussed, and useful ways to view these distinctions are suggested.

Palmer (1978) treats the analogical/symbolic distinction as a distinction between information "intrinsic" to the representation and information "extrinsic" to it. The representation is an analog of the represented world when the relations of interest are intrinsic to the representation. A representation is intrinsic whenever a representing relation has the same inherent constraints as the relation it represents. The continuous/discrete distinction (which is often confused with the analogical/symbolic distinction) is really about the "grain size" or "acuity" that must be captured in the represented world (Rumelhart & Norman 1988).

A representational system consists of both data structures and operations. The data structure can be represented through different representational formats that map best into the set of operations to be performed upon it.

The relevance of this analysis to the design of displays should be readily apparent. If the funciton of a display is to communicate information and to ensure efficient processing of this information, the display's designer must map informaton structure into display attributes in a way that suits both the information to be represented and the operations to be performed on it.

We can learn much about how to organize, access, and manipulate displayed information from current research in cognitive psychology, including studies of pattern recognition, visual search, cognitive maps (Chase 1986), and perceptual organization.

Cognitive psychologists are making serious attempts to go beyond the descriptive laws of the Gestalt psychologists to understand perceptual organization in information-processing terms (e.g. Kubovy & Pomerantz 1981; Boff et al 1986). Particularly relevant are theoretical accounts and empirical studies on grouping, dimensional interactions, analytic and holistic processing, perceptual relations between global and local aspects of visual patterns, top-down processing (Treisman 1986), and the role of spatial-frequency analysis in form and object perception (Ginsburg 1986).

The importance of the Gestalt laws of grouping for organizing display informatin is well recognized (e.g. Helander 1987; Foley & Moray 1987). A better application of these laws can benefit from recent research based on performance measures of grouping (e.g. Pomerantz 1981; Treisman 1985).

How physical dimensions are combined to form perceptual dimensions has been studied extensively by Garner and his colleagues (e.g. Garner 1974, 1978). Garner distinguishes between separable, integral, and configural dimensions. Stimuli varying along integral dimensions are perceived as unitary entities, whereas those varying along separable dimensions are perceived in terms of distinct dimensions or attributes. Configural dimensions interact so that their combination produces a new emergent feature (e.g. closure, symmetry). Integral dimensions facilitate performance when they are perfectly correlated and selective attention to either dimension is impossible. Separable dimensions permit selective attention to either dimension, but they do not facilitate performance when they are redundant. With configural dimensions, performance is dominated by the new emergent feature. It has been suggested that emergent properties are perceived directly (e.g. Pomerantz 1981).

Do the earliest perceptual stages encode unitary wholes, which are later analyzed into parts and properties, or are the parts registered first and then synthesized to form the objects we are aware of? This unsettled issue has generated a wealth of empirical research. The feature-analytic approach provided some evidence for the role played by parts and properties in perception (Treisman 1986). The global superiority phenomenon (Navon 1977, 1981) supported the primacy of holistic or global processing; but other researchers demonstrated important boundary conditions of the phenomenon (e.g. Hoffman 1980; Kinchla & Wolfe 1979; Miller 1981) and provided finer analysis of the perceptual relations between global and local aspects of visual patterns (e.g. Kimchi & Palmer 1985; Kimchi 1988).

The role of prior knowledge or expectations in perception has been studied. Most current models of object and event perception see it as an interactive process between bottom-up (data-driven) processing and top-down (conceptually driven) processing (e.g. Rumelhart 1977; Treisman & Schmidt 1982).

Current Application Research

A major line of application research focuses on representational issues. Typical questions concern selection and evaluation of display symbology, the advantages of one type of format over another, and the benefits of pure vs mixed formats in complex displays.

Analog formats are compared to digital. Analog formats in this context are loosely defined and refer most often to spatial, continuous representation. In many cases analog formats and graphic representations are referred to interchangeably. Traditional analog formats include bar graphs, dot clusters, and dials. Digital formats include alphanumeric coding such as digits, letters, and word names. The relative efficiencies of these formats have been investigated with a variety of tasks. For example, Boles & Wickens (1987) compared analog (bar graphs), digital, and verbal formats in a numerical judgment task and found that analog indicators were responded to more quickly than were digital or verbal indicators. Schwartz & Howell (1985) compared performance in a simulated hurricane-tracking task under conditions in which position information was presented either graphically or digitally. Subjects performed better using graphic displays, particularly under conditions of rapid change. Bauer & Eddy (1986) studied representation of command language syntax. They compared the use of special metacharacters and graphic representations to represent grammatical relations. They found the graphic representation to be superior both during learning and in a reference task.

Boles & Wickens (1987) found that tasks requiring the integration of display elements benefited from pure-format display, while dual tasks benefited from a mixed-format display.

For use in displays one would like to select symbols that represent well and are maximally dissimilar to one another. Graphic symbols, especially pictographs, may be preferred over alphanumeric symbols because the resemblance between the shape of the symbol and that of the object it represents can be exploited. This can be especially beneficial under heavy memory demands. However, intra-set similarity among pictographs can increase search and identification time. For example, Remington & Williams (1986) used a single-target visual task to evaluate a set of CRT symbols for a helicopter situation display. They found numeric symbols superior to graphic symbols. The authors attributed their finding to the familiarity and discriminability of the numeric symbols on the one hand, and to a high degree of intra-set similarity among the graphic symbols on the other. Recently, Workman & Fisher (1987) proposed a new metric of similarity based on the degree of overlap between "fuzzy pictures" of the symbols. The similarity ratings derived from this metric can be used to select the most discriminable subset from a set of meaningful symbols.

A popular solution to the problem of presenting multidimensional correlated information to operators of complex systems has been the integral, object-like display. Integral display formats use several dimensions of a single object to portray system status (e.g. polygons, schematic faces). Separable display formats use separate univariate displays, either in the traditional digital (alphanumeric) formats or by using the same dimension of several objects to display mulitivariate information (e.g. bar graphs). Many studies have found integral displays superior to separable displays when the data variables are highly correlated and/or when integration of data from a number of sources is required by the operator before a decision can be made (e.g. Goldsmith & Schvaneveldt 1984; Carswell & Wickens 1988; Beringer 1985; Beringer & Chrisman 1987; Boulette et al 1987).

The superiority of the integral, object-like display can be attributed to two properties of human perception: (*a*) The human perceptual system has a limited ability to process a single dimension with multiple objects at the same time, while it is capable of processing in parallel several dimensions of a single object (e.g. Lappin 1967; Kahneman & Treisman 1984). (*b*) Global or holistic features can be processed faster than local features (e.g. Navon 1977, 1981; Pomerantz 1981). Object-like displays change their global form to convey relations in system states, so such displays may be globally processed (Munson & Horst 1986). However, the advantage of an integral display can be nullified under certain conditions. For example, Coury and associates (1986a) demonstrated that when the system state was certain, the operator was able to classify more quickly integral than separable displays; but when the system state was uncertain, separable displays were superior to the integral ones.

An important determinant of integral display effectiveness is the attentional requirement of the task. For example, Casey (1987) compared integral and separable displays in the detection and diagnosis of failure for systems whose variables were related either by correlation or by causality. For both types of systems separable displays were superior. The diagnosis task required focusing on the components of the display in order to identify the cause of failure. Thus, while holistic processing supported by object-like display is useful for analysis of overall status, it is detrimental when the task requires selective attention, even when the system components are strongly interrelated.

A considerable amount of research effort has been devoted to the relation between the type of display (integral vs separable) and two factors: the structure of the information to be presented (correlated vs noncorrelated) and the nature of the task (integral vs nonintegral). The physical dimensions used to represent the information received much less attention. Granted that there is no one-to-one mapping between physical and perceptual dimensions, it should be important to consider how physical dimensions interact to form perceptual dimensions in terms of their integrality, separability, and configurality (see above). A step in this direction has been taken recently by Barnett & Wickens (1988).

The importance of a compatibility between the format of the displayed information and central processing codes, particularly in working memory, is well recognized (e.g. Wickens 1987). Once visual displays are used to represent complex systems, there is greater concern about the compatibility between the displayed information and the mental model the human operators have of the systems. Displays of complex systems can support or enhance human performance if they match human mental models of the system, or if they help to shape the correct mental models (e.g. Woods 1986; Coury et al 1986b; Eberts & Schneider 1985; Eberts 1986; Sanderson 1986).

A related line of research focuses on representation of spatial information by computer-generated graphics. In natural or even pictorial viewing the viewer can rely on the structure of correlated attributes in the physical world to provide multiple cues about the event and the space in which it occurs (Hochberg 1986). Owing to the synthetic nature of computer-generated graphic representations, such information is missing. In order to communicate spatial information, the designer of such representations must consider both the relevant physical structure (e.g. various perspective cues) and the relevant perceptual processes. One attempt to develop more efficient displays for representing three-dimensional information on two-dimensional screens produced the perspective display for air-traffic control (Ellis et al 1987; McGreevy & Ellis 1986). Use of the perspective display, considered more "natural" than the conventional plan-view, improved decision time and avoidance performance (Ellis et al 1987).

Summary

The most frequent empirical finding is an interaction of displays with tasks. The importance of task requirements in perceptual processing has been manifested in basic research as well (Treisman 1986). How, then, might one go about developing guidelines for the design of complex visual displays? This question brings us back to the representational issues discussed at the beginning of the section, suggesting an answer in the following general terms:

1. Determine which aspects of the represented world (e.g. a complex dynamic system) are to be captured within the representing world (i.e. the visual display).
2. Determine how the selected aspects shall be represented.
3. Recognize that items 1 and 2, above, depend critically upon task domain. This requires a coherent analysis of task requirements in terms of human information processing.

THE STUDY OF MENTAL WORKLOAD

Key books and comprehensive chapters have been published recently on mental processing and response limitations in the performance of tasks (Hancock 1987; Gopher & Donchin 1986; O'Donnell & Eggemeier 1986; Kantowitz 1987; Hart 1986).

Since the review of mental workload by Wickens & Kramer (1985) the need to strengthen the theoretical basis of this research has been increasingly recognized.

Technological Need

Human operators are today required to fulfill monitoring and decision-making roles at the center of highly automated systems. They are confronted with multiple and diversified sources of information, updated at high rates. This state of affairs naturally raises the question of capacity limitations. What are the boundaries of the human ability to attend to sources of information, to process, transform, decide, and carry out the necessary responses? How much information can be provided and in what form? What are the risks and costs of exceeding the limits?

Theoretical Foundations

Contemporary efforts to understand the human processing system follow two major courses: One is an attempt to develop computational models that can mimic basic behavioral phenomena and thus elucidate limitations in terms of the architecture of the underlying psychological processes. A second course studies intensive aspects of behavior and attempts to complement the analysis of structure by introducing considerations of resource scarcity and energy modulation. Both approaches emphasize the development of models linking the findings of behavioral research with those in the physiological and biological sciences.

COMPUTATIONAL APPROACHES Most significant has been the development of parallel distributed processing (PDP) models (McClelland & Rumelhart 1985, 1986; Rumelhart & McClelland 1986; McClelland 1989). The PDP approach holds that the brain's processing system consists of a collection of simple processing units, each interconnected with many other units. The units take on activation values and communicate wih other units by sending signals modulated by weightings assoicated with the connections between the units. Units are organized into modules that receive input from other modules. The units within a module are richly interconnected. A mental state is a pattern of activation over the units in some subset of modules. Alternative mental states are simply alternative patterns of activation over the modules. Information processing occurs through a series of mental states (McClelland & Rumelhart 1985, pp. 161–62).

This general approach is accompanied by rigorous criteria and construction rules. It has successfully modeled behavior in a variety of tasks, including learning and memory, language understanding and production, and motor behavior.

ENERGETICS How do energy factors regulate human information processing? This course of research represents a revived and revised interest in one of the classical issues of psychology—accounting for motivational and intensive aspects of behavior, as opposed to structural and directional aspects. A good summary of the present state of knowledge in this area can be found in *Energetics and Human Information Processing* (Hockey et al 1986).

Work in this category covers such topics as: slow and fast phase diurnal fluctuations in response efficiency, sustained attention, effects of voluntary effort, changes in rate as contrasted with quality of responses, mobilization of attention, and response to stress. Behavioral evidence for such changes often correlates with intensity modulations of physiological processes, such as fluctuations in levels of arousal, rhythmicities of activity cycles, event-related brain activity, and responses to pharmacological interventions. Neurobiology has demonstrated evidence of discrete neurotransmitter systems with specifc information-processing functions (Pribram & McGuinness 1975; Pribram 1986; Posner & Rotbart 1986; Peterson et al 1988), and researchers have proposed links between these systems and constructs emerging from information-processing models (Gopher & Sanders 1984; Lavie et al 1987;

Sanders 1986; Van der Molen et al 1987; Coles & Gratton 1986; Posner & Rotbart 1986). Physiological mechanisms may function as separate processing resources (Gopher & Sanders 1984; Friedman & Polson 1981) or act as gain factors to vectors of computational operators (Wickens 1986; Gopher 1986; Posner & Rotbart 1986).

Work in computational structure and work in energetic factors have identified different dimensions of increased task difficulty and different causes of performance deficit. Structural interpretations emphasize the contribution of factors such as the number and type of transformations that must be carried out in sequence, or conflicts and confusions between inputs, throughputs, and outputs of processing activities (Navon 1985; Navon & Miller 1987). Energetic interpretations adopt the term "resources" to define the processing facilities at the disposal of the human "operator." Resources can be invested in shares and actively allocated to the performance of tasks. Resource models emphasize capacity limitations—the scarcity of energy and space—as the cause of performance deficits under increased demands (Norman & Bobrow 1975; Navon & Gopher 1979; Wickens 1984; Gopher 1986).

Most contemporary proponents of the resource approach identify several relatively independent resources (Wickens 1984; Gopher 1986). There is also, however, a modern single-limited-resource approach, which emerges from the distinction between automatic and controlled modes of processing. Controlled processess are postulated to be attention demanding, slow, and effortful, while automatic processes do not require attention and can proceed in parallel. This model was orignally proposed by Shiffrin & Schneider (1977) and has recently been elaborated by Schneider (1985a).

Real-life tasks require processing in both the automatic and the controlled modes. The load is determined by the proportions of the two modes. This approach has been tested in many studies (see Fisk et al 1987 for a recent review). In essence, this model integrates the computational and energetics perspectives. Its basic postulates concern the organization of computational processes. However, operation at different organizational levels has its corresponding energetic costs.

Current Application Research

While basic research is still brooding over the nature of the central limitations and the best approach to modeling them, engineering psychology has launched into development of techniques to assess workload. Apparently, the intuitive appeal of the limited-capacity concept, coupled with the increasing pressure from the field, were strong enough to suppress ambiguities and drive the conduct of a large number of empirical and application-oriented studies. Most of these accept the existence of a central limitation and do not question its general nature. They then consider how to develop standard measurement scales, interpret the obtained values, and compare scales (Hart 1986; O'Donnell & Eggemeier 1986; Wierwille et al 1985).

Three classes of measures have been developed to assess workload: behavioral, physiological, and subjective.

BEHAVIORAL MEASURES Behavioral measures derive an index of workload from elements of operator performance. The most popular and widely researched behavioral approach has been the "Secondary Task" technique. In this technique the level of performance on one of two concurrently performed tasks is used to index both spare capacity and, by complementary inference, the load imposed on the central processor by the task with which it is time-shared (see Wickens & Kramer 1985). In recent years various types and numbers of secondary tasks have been employed. Types of tasks vary with the researcher's theory about the dominant causes of load. They follow the progress of information-processing models. The number of tasks, or the employment of a battery of different secondary tasks, is a more recent development influenced by the multiple-resource view. It fosters the idea of creating a load profile for tasks to index differential resource loadings of component processes.

Representative studies have employed secondary tasks claimed to provide separate measures of the load share of perceptual, mediational, or response processes (Wierwille et al 1985; Gopher & Braune 1984; Derrick 1988). Other experiments contrasted spatial and verbal tasks, related to right- and left-hemisphere-localized processes (Wickens et al 1984; Carswell & Wickens 1985; Friedman & Polson 1981; Friedman et al 1982). A third group of experiments studies the load consequences of varied versus consistent relationships between S-R components, reflecting controlled or automatic operation modes (Vidulich & Wickens 1986; Fisk & Schneider 1984).

A typical outcome in such studies is a performance interference profile, in which some tasks show larger interference under time-sharing conditions. It is interpreted as revealing the locus of load on the central processor (Wierwille et al 1985; Derrick 1988). A good application of this strategy is the battery of criterion tasks for the measurement of workload, developed by the US Air Force workload branch at Wright Patterson, for use in the design and procurement of systems by the Air Force (Schlegel et al 1987). The selection of tasks in this battery follows the dimensions of resources proposed by Wickens (1984). It includes 9 leading tasks, presented in a total of 25 different configuartions, varying in modality of presentation, temporal structure, type of required transformations, and mode of response.

PHYSIOLOGICAL MEASURES The study of physiological measures concentrates upon indexes of the physiological activity associated with information-processing tasks. Two factors have influenced the increase of interest in this approach [e.g. see the special issue of *Human Factors* edited by Kramer (April 1987)]: (*a*) the growing emphasis and accumulated knowledge on the relationship between physiological mechanisms and information processing constructs, and (*b*) our enhanced ability to obtain accurate physiological measures in field conditions with little interference to normal operator activity.

Two major classes of physiological measures have been developed: general indexes of arousal and processing effort, and measures locked to specific processing activities. Contemporary studies of general measures focus on cardiovascular activity and pupil dilation. For example, Aasman et al (1987), using spectral analysis of heart-rate variability, have shown correspondence between increased amplitude at 0.10 Hz and increased memory load. Vincente et al (1987) showed correspondence between sinus arrhythmia and demands of manual control. Both cases led to the development of portable measurement equipment for field work. Beatty (1982, 1986) has shown the relationship between pupil dilation and the change of difficulty on a variety of tasks, including memory, perception, and motor control.

Physiological measures of load corresponding to specific processing activity have concentrated primarily on event-related brain evoked potentials (ERP). For example, the amplitude of the P300 component of the ERP varies with the level of encoding and central processing demands in a simulated flight mission (Kramer et al 1987). Mangun & Hillyard (1987) used six ERP components localized at a four scalp regions to describe gradients of visual and spatial attention. Bauer et al (1987) used changes in amplitude of the P1–N1 components to index the selective load of memory and encoding processes. Both ERP measures and general physiological indexes have been included in the workload test battery developed by the US Air Force (Wilson & O'Donnell 1988).

SUBJECTIVE MEASURES Performers can be asked to indicate the difficulties experienced in the performance of the evaluated task. These estimates are easy to obtain and have high face validity, but they suffer from two major drawbacks. (*a*) The conscious experience they reflect covers only a small portion of the information-processing activity of interest in the assessement of workload. (*b*) Subjective biases as well as intrá and interindividual variability affect how people quantify their experience (Gopher & Braune 1984). Nevertheless, the use of subjective measures increases in popularity, and there have been two recent large-scale research efforts to construct standard workload rating scales based on subjective judgments: the NASA-TLX (*T*ask *L*oad inde*X*: Hart & Staveland 1988) and the US Air Force SWAT (*S*ubjective *W*orkload *A*ssessment *T*echnique: Reid & Nygren 1988).

Both TLX and SWAT have been tested on a wide range of laboratory and real-life tasks (primarily in the aviation environment). They correlated highly with each other and were sensitive measures of the subjective experience of load (Vidulich & Tsang 1986).

Summary

Each class of measures has its advantages and disadvantages as an index of workload. Behavioral measures are the final product of the system, the components of which are hard to decompose. Employment of secondary tasks may be obtrusive and introduce spurious consideration of attention policy. Physiological measures are less direct and are influenced by many variables not related to information processing. Subjective measures are influenced by irrelevant variables and reflect only conscious experience.

In absence of a formal model of workload, or a set of decision rules, most of the studies cited above used several measurement classes in conjunction. This strategy has complicated the situation by producing different load estimates of the same task, which have often dissociated. Current research has limited power in resolving dissociation, although several attempts have been made (Gopher & Braune 1984; Vidulich & Wickens 1986; Coles & Gratton 1986; Ye & Wickens 1988).

Which measurement strategy should be used to assessment mental workload? We cannot and should not yet attempt to answer. In spite of the massive research conducted in this area, we remain at the stage of demonstration. We know more about the structure of tasks and the variables that may influence processing difficutly, but we have little ability to estimate and predict limits. We know little about how the different manifestations of load relate to one another, or about how separate elements that influence load interact.

Yet these are the questions engineering phychology must answer. System designers want to know how close is the performer to his limits and how much load can be alleviated by technological innovation. Engineering psychology is now able to give only partial and fragmented answers. Comtemporary applied research has exhausted the degrees of freedom provided by the crude theoretical models that have guided it. Progress now depends on a better theoretical understanding of the human processing system.

TRAINING OF COMPLEX SKILLS

Technological Need

With the advance of automation and robotics the proportion of unskilled jobs diminishes rapidly while that of professional jobs increases. Performers must often acquire advanced knowledge and moderate expertise before entering the operational environment. On-the-job training is either impossible, too time consuming, or too expensive. Moreover, task complexity and the evolution of technology at the work station often require continuous training, reorganization, and upgrading of existing skills.

At the same time, rapid progress in simulation, artificial intelligence, and microprocessor technology paves the way to the development of powerful, inexpensive training devices to meet training objectives.

Theoretical Foundations

The changing roles of human operators at the work station match well the interests of contemporary psychology. Within the general study of cognitive processes is a special focus on knowledge representation and the modeling of expert behavior. Appropriately, the training problem addresses how to develop, maintain, and reformulate expertise in the most efficient way.

Contemporary theories of expert behavior, anchored in the framework of cognitive psychology, concentrate on information-processing concepts (Anderson 1981, 1985; Adams 1987). The focus is on the representation and organization of knowledge in, and methods for its retrieval from long-term memory. Expertise is conjectured to constitute a well-roganized set of schemas in such specific domains of behavior as solving probelms of Physics, computer programming, troubleshooting in mechanical and electrical systems, proficient typing, and piloting airplanes. Interest lies in the final form of representation and in the operation rules of expert knowledge, as well as in the processes of arriving at this stage.

The modern instantiation of the distinction between conscious and nonconscious determinants of skill acquisition manifests itself in the study of top-down strategies of acquisition and represenation (Chase & Ericsson 1981; Anderson 1981; Moray 1986) as compared with new models of bottom-up conditioning through reinforced experience (McClelland & Rumelhart 1985; Schneider 1985b).

Research in top-down processes has shown the influence of encoding strategies, efforts to assimilate new information in exisiting well-organized knowledge bases, and retrieval techniques on the development of expertise. There is also an active interest in the role of mental models developed by the performer in the guidance of efficient behavior (Gentner & Stevens 1983).

Bottom-up processes of acquisition are being investigated by the PDP group, which views the establishment of knowledge bases as a process of emerging patterns of activation and inhibition among multiple interconnected processing modules (McClelland & Rumelhart 1985). Similar priniciples guide the research on the development of automaticity through experience with consistent mappings between stimulus and response (Schneider 1985a). Both types of bottom-up modeling approaches search for physiological counterparts to anchor their constructs and organization rules in the reality of the nervous system.

Implication for Applied Research

Several applications of top-down principles have been studied. One line of investigation focuses on the development of mental models. The mental-model construct has become a key concept in the training of complex skills (Gentner & Stevens 1983; Moray 1987; Eberts & Schneider 1985; Gagne & Glaser 1987). A mental model is loosely defined as an internal representation of the structure of a complex system or the demands of a task, together with a set of heuristics or rules that may guide problem solving and performance. Errors and inefficient performance can be frequently traced to faulty mental models (Moray 1987; Rumelhart & Norman 1981). Gagne & Glaser (1987) identified four tactics for encouraging the use of mental models in the acquisition of skill: (*a*) discovery, utilization, and elaboration during training of everyday models that trainees may bring to the training environment; (*b*) tracing the types of models a trainee develops during the acquisition of expertise, and using these in training; (*c*) deliberate introduction of "good" mental models; and (*d*) taking advantage of an individual's current model by using examples, counterexamples, and situations in which that model can be tested.

The mental-model concept has been explored in troubleshooting in engineering systems (Morris & Rouse 1985), pilot judgment training (Buch & Diehl 1984), manual control of highly dynamic systems (Eberts & Schneider 1985), spatial ability of air-traffic controllers (Schneider et al 1982), and complex supervisory tasks (Sanderson 1986).

Other applications of top-down cognitive principles attempt to construct training situations that will facilitate encoding, representation, retrieval, and interaction with knowledge bases. Many studies of this type were conducted in the context of human-computer interaction (Bosser 1986). Typical examples are mastering programming languages (Williges et al 1987), carrying on dialogs with computers (Streitz et al 1987; Wood & Wood 1987), operating data entry devices (Gopher & Raij 1988; Gopher 1984, 1987; Gopher et al 1985), using complex software, and interacting with intelligent systems (Grudin & Barnard 1984; Boehm-Davis et al 1987; Bransford et al 1986).

Just as important are the attempts to use the emerging principles of cognition for the development of training-oriented task analysis. Task analysis has always been a major concern of any training program. What are the task's basic components, and what are the best ways to segment them in the course of training? This has been the traditional part-whole issue (Adams 1960; but see also Wightman & Lintern 1985, for a recent discussion). The significance of this question increases as the complexity of tasks advances. In complex tasks the gaps between novice and expert performance are greatly increased and the task in its final form is frequently beyond the capability of the beginner.

Some method of task analysis is either explicitly or implicitly embedded in every training program. The more overt, systematic, and objective it is made, the lower the probabilty of introducing ambiguity and inconsistency to the training situation. Systematic research on this issue is sorely wanting.

The focal point for one proposed approach has been an analysis of the final knowledge base of the expert, which is followed by hierarchical decomposition of the principles, rules, goals, and subgoals of this knowledge (Frederiksen & White 1989; Ryder et al 1987; Nave-Benjamin et al 1986). Another approach concentrates on decomposing task demands in terms of the processing mechanisms involved and the load on each mechanism (Mane et al 1983; Logie et al 1989). Proponents of the distinction between controlled and automatic processes promote a third approach, based on segmentation to components by identifying the consistently vs variably mapped task elements (Schneider 1985b; Fisk et al 1987). A fourth approach proposes decompostion by identifying task elements amenable to being the focus of strategic voluntary shifts of attention (Gopher et al 1989). Research work in all these directions is preliminary. Development of task-decomposition methods for training remains an important challenge for future research.

Training of High-Workload Tasks

While the training research reviewed thus far is primarily concerned with the structure and content of expert behavior, there is also an active interest in the accompanying attention costs to performance. Skilled behavior has been associated with increased automaticity, relegation of authority to peripheral mechanisms, and decreased involvement of high-level, attention-demanding and time-consuming processes. Automaticity may lead, in turn, to an increase in the rate of performance, reduction of attention demands by the task itself, and better ability to attend to secondary or new task elements (Fitts & Posner 1967; Welford 1968).

One approach to this issue follows the theoretical distinction between controlled and automatic processes. Controlled processes are claimed to be attention demanding, sequential, and limited, while automatic processes are argued to be parallel and attention free. According to this approach, reduced costs are concomitants of automaticity developed by repeated exposures to consistent stimulus-response mappings. Tasks that comprise a larger portion of consistent elements will be less limited and less attention demanding. In contrast, tasks that include many elements that vary in their mapping will impose high load even after prolonged periods of training. These arguments have been supported in several empirical studies (Fisk et al 1987; Schnieder (1985b).

An alternative, though not exclusive, approach takes a more active and direct view of the relationship between attention processes and the development of expertise. The theoretical anchors of this approach are the study of workload and the concept of voluntary control of multiple attentional resources (Gopher & Donchin 1986). Processing demands of complex tasks are described by their load vector on different resources and task elements. Proficient performers are hypothesized to develop efficient attention allocation and attention mobilization strategies as part of their expertise. One objective of these strategies is to maximize the match between the demand profile of the task and the individual capabilities of the performer. A second objective is to enable the performer to mobilize efforts and change strategies when task conditions vary. The main arguments of this approach have been summarized in two recent papers (Gopher et al 1985; 1989). A similar view has been proposed by Mane & Wickens (1986). Experiments to test the approach were conducted on subjects practicing complex computer games and on the training of flight skills (Gopher et al 1988).

The Technology of Training

The emphasis on cognition has had interesting influences on the technology of training, most significantly in the arena of complex skills and the design of simulators. Emerging historically from the training of vehicle control skills (piloting airplanes, driving cars, and navigating ships in rough seas), simulators are being employed nowadays in the training of a wide and diversified range of tasks in industrial, military, and office environments (Flexman & Stark 1987). Formal principles for the construction of training simulators have not yet been elaborated. In the absence of sufficient theoretical understanding of skill acquisition and transfer processes, the dominant design rule over the years has been physical fidelity: the greater the similarity between the physical characteristics of the simulator and the operational environment, the larger the training value of the simulator.

As systems and tasks have become more complex and demanding and the operational environments more extreme, so have the challenges and costs of constructing training simulators increased. These developments have made the "physical fidelity" principle impossible or too expensive to achieve. They raise the issue of the cost effectiveness of increased sophistication (see "How much do you want to pay for this box?", C. Hopkins 1975). The situation has generated a growing interest in establishing alternative design principles based on the skill structure and the functional and psychological demands of the task. Such characteristics can be simulated at various levels, even at low levels of physical fidelity (Roscoe 1980).

Initial efforts in this direction lacked the theoretical framework and the technological tools for success; but recent developments in microprocessor technology, on the one hand, and the accumulated knowledge in cognitive psychology, on the other, may soon be joined to develop better designs. Microprocessors are rapidly becoming powerful, inexpensive machines capable of simulating complex situations. Cognitive psychology may supply the tools for the analysis of expertise and delineate the route from novice to expert performance.

Although work in this area is still embryonic, several successful applications have been reported. There is also a growing interest in the potential of part trainers based upon cognitive analysis. Halff et al (1986) review several examples involving the training of military skills. Discussing the cognitive demands of four groups of tasks (maintenance, tactics, piloting, and air-traffic control), Halff et al describe principles and tools developed to train personnel. The cognitive components dealt with included memory and semantic networks, understanding of dynamic systems, perceptual capabilities used to judge relative motion, and synthesis of spatial and orientational components required to perform air-traffic control functions. In all cases, the trainers can be conceived of as part simulators of the skill components and cognitive demands of the represented task. Experience with these trainers led to substantial improvement in task performance.

A forthcomming issue of *Acta Psychologica* (ed. Donchin 1989) is a compendium describing the results of an international collaboration. Headquartered at the University of Illinois and conducted simultaneously at 9 laboratories in the United States, Canada, United Kingdom, and Israel, the project sought to develop learning strategies to be embedded in the algorithms of complex computer games to improve players' acquisition of predetermined skills. The task was a highly complex, dynamic, and difficult computer game, codesigned by all the participant laboratories. It combined difficult manual, visual, attention, memory, and decision-making skills. Laboratories differed in their theoretical emphases, proposed approaches to the decomposition of the complex task, and methods of training.

Representative strategies concentrated on part tasks corresponding to components of the expert knowledge base (Fredriksen & White 1989), on voluntary control of attention (Gopher et al 1989), on training of visual skills (Shapiro & Raymond , 1989) and on improvement of manual control strategies (Newell et al 1989). From several perspectives the project may serve to clarify and underline many of the theoretical and practical issues raised here. More specifically, it indicates the urgent need for a theory-based approach to task analysis, demonstrates the powerful influence of well-designed training, and shows that practice, unless it is properly introduced, does not make perfect.

CONCLUDING REMARKS

The gaps between basic and applied research are narrower than we had expected them to be. Contemporary basic research has grown more attentive to problems raised at the field level. Application efforts have begun to turn more often to theory, in an attempt to increase their influence upon the deveopment of technology. Consequently, there is considerable interest in establishing and maintaining an active dialog between basic and applied research.

In each of the three problem areas reviewed, we detected ongoing shifts in emphasis. The area of visual displays is shifting from an emphasis on basic psychophysical functions to problems of complex perceptual organization and functional representation of multidimensional sources of information. Workload research is marked by increased emphasis on a multitask, multimeasures approaches anchored in multiple-resource theoretical models. There is also a greater focus on physiological and subjective measures than on performance indexes. The training area is undergoing a fundamental reformulation dictated both by the transition from behaviorist to cognitive models of learning and by the new types of skills required at the work station.

Better task analysis methods are needed in each of the problem areas. Task analysis enables the applied worker to relate problems encountered in the field to the knowledge bases of science. Most task analysis methods developed over the years (Fleishman et al 1984) suffer from major drawbacks. They may not be linked explicitly with any theoretical model of performance and/or they may advocate a single generic method for multiple application objectives.

A good task analysis method should be specific to application goals and have clear ties with the constructs of a theory of performance. The dimensions of task analysis relevant to training issues differ considerably from those of interest to workload assessment or to the efficient display of information. Task analysis methods must thus be developed within the context, models, and concerns of a specific problem area. At present, the absence of such methods leaves the field seriously handicapped.

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