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Human Cognition and Information Display in C3I System Tasks

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It is widely recognized that the growing demands of modern warfare strain and in some cases exceed human cognitive capabilities. Although modern command, control, communication, and intelligence (C3I) systems incorporate a number of advanced design concepts to reduce the burden on operators, it is essential that they retain certain key controlling functions. Therefore, efforts toward improving our understanding of how various design concepts affect human (and overall system) performance must continue. In particular, it is not always clear how general design principles relate to the specific kinds of critical tasks performed by operators in C3I systems.

The purpose of this report is to present a highly selective review of the literature on C3I tasks, display principles, and human information processing functions with an eye toward identifying promising variables or concepts for evaluation in a simulated system

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context. The review is organized into three sections. The first discusses various features of C3I tasks and the particular cognitive requirements that each poses for the operator. The second section explores particular cognitive research domains (e.g., mental capacity limitations and time-sharing, conditions for parallel processing, and irrelevant information and information processing) that bear on the task requirements identified above. Finally, the third section briefly discusses implications for research into specific display design issues.

HUMAN COGNITION AND INFORMATION DISPLAY IN C3I SYSTEM TASKS

CONTENTS

HUMAN COGNITION AND INFORMATION DISPLAY IN C3I SYSTEM TASKS

Background

System Design Issues and Trends

The fact that advances in technology have increased the operator's information processing burden in modern Command, Control, Communication, and Intelligence (C3I) systems has been widely recognized for some years now (Cohen & Freeling, 1981). Warfare technology moves ahead at an increasingly rapid pace, information gathering and transmission capabilities put more knowledge at the operator's disposal, and computer processing and display technologies provide more options for dealing with this massive and ever-changing knowledge base (Knapp, Moses, & Gellman 1982; Wohl, 1981). Additionally, military doctrine is changing in the direction of the distributed decision-making concept whereby field commanders at the small unit level (e.g., company and below) function relatively autonomously within the constraints of an overall tactical plan (Harris, Fuller, Dyck, & Rogers, 1985; Marvin, Harris, & Fuller, 1985; Noble & Truelove, 1985). While this concept is designed to provide greater flexibility and reactive capability in the course of battle, it also increases the need for coordination among multiple decision-makers--an added informational burden.

In view of the well established generalization that humans are limited in their ability to process information and to make certain kinds of judgments and/or decisions based on it (Payne, 1982; Sage, 1981), much attention has been given to design issues such as man-machine function allocation (Meister, 1985; Meister & Sullivan, 1979; Williges, Ehrich, Williges, Hartson, & Greenstein, 1984), decision aiding (Christen, 1980; Fischoff & Bar-Hillel, 1980), and adaptive computer aiding (Morris, Rouse, & Frey, 1984; Rouse & Rouse, 1983; Samet, Weltman, & Davis, 1976). In other words, it is recognized that the growing demands of modern warfare strain and often exceed human cognitive capabilities, and the issue becomes how and where to provide machine assistance. For a variety of reasons, however, it is unlikely that the human will relinquish ultimate control to the machine, even where total automation is possible. The commander must at a minimum retain a monitoring function, stand-by skills, and an override or sign-off capability. Therefore, it is essential that efforts continue toward improving our understanding of how various design concepts for C3I systems affect human (and overall system) performance in a semi-automated mode.

Relations Among Tasks, Displays, and Cognitive Processes

One obvious focal point for such activities is the traditional area of display design. Clearly, if the human is overburdened with information and help is to be found in machine design, a logical place to start is with the interface between available knowledge about the environment and the human perceptual/processing system. A long history of human factors research has established that (a) some ways of organizing, presenting, and coding information are superior to others from the perceiver's standpoint, (b) that the amount and nature of the advantage is highly dependent on the perceiver's task (Hitt, 1961)--that is, what s/he has to do with the information--as well, obviously, as on the sensitivity of system output to human performance, and (c) the degree of compatibility that exists between the structures afforded by theinformation display and the cognitive structure of the human processor is an important task feature (Fitts & Seeger, 1953; Wickens, Sandry, & Vidulich, 1983). To the extent that we understand what aspects of a task are most important to system performance and how the human perceiver/processor uses available information in performing those functions, we are in a better position to develop and test concepts for improving display design (Landauer, Dumais, Gomez, & Furnas, 1982).

At the present time, our understanding of these relationships among displays and cognitive task features is severely limited for the kinds of situations that commanders are (and will be) encountering in advanced C3I systems (Sage, 1981; Wohl, 1981). It is generally assumed, for example, that since information overload, clutter, etc. are problematic, display simplification is a worth goal (Engel & Granda, 1975; Knapp, Moses, & Gellman, 1982). Yet it is not entirely clear what simplification means from the perceiver/processor's standpoint, or to what extent it varies with task requirements. For example, certain enhancement techniques (such as highlighting) simplify the discrimination between relevant and irrelevant information but add to the total information in the display. Similarly, enhancement of items that activate appropriate interpretive "schema" in the observer would theoretically simplify the decision process (Noble & Truelove, 1985), but they could just as easily cause confusion or ambiguity if not matched perfectly to the individual's subjective organization. Rasmussen (1980) supports the increasingly popular concept of providing information selectively based on the operator's cognitive needs in light of task demands. The problem is that the state of the art in cognitive task taxonomizing is still extremely primitive and controversial (Companion & Corso, 1982; Fleishman & Quaintance, 1984; Meister, 1985). In short, there is currently no way to predict reliably what an individual's cognitive needs will be in a particular situation.

Nor is it clear that simplification, even if meaningfully defined, is always beneficial. The Vehicle Integrated Intelligence (V(INT)2) and other adaptive aiding concepts, for example, are based on the philosophy of providing "...the minimum amount of information that will enable the commander to respond effectively to the battlefield situation" (Harris et al., 1985). This presumes a fairly precise knowledge of what the operator needs at each point in a sequence of events, and the selection of what information to show him is based largely on a logical analysis of the typical scenario as it unfolds (Harris et al., 1985; Marvin et al., 1985). While it would be difficult to fault this rationale as a general concept, there may be situations in which (or individuals for whom) it is useful to preserve the subtleties of an evolving spatio-temporal pattern of events in literal form during the course of a battle in preference to a simpler, more efficient organization, even though the human cannot process all the information. Giving the operator access to this pattern on demand overcomes the problem in part but only at the cost of another cognitive task element: decision. And finally, even though human performance is enhanced by a particular display design principle such as simplification, one must consider whether the improvement in total system effectiveness is sufficient to justify the cost and/or any other unanticipated side effects that implementation might cause.

The point is, it would be useful to know what impact various display design principles have on the performance of cognitive functions typically (or even occasionally) reserved for the human in C3I systems, and what, if any, aspect of overall system performance is likely to suffer if these principles are ignored. This idea is, of course, by no means new (Meister & Sullivan, 1979). But despite the fact that it has produced a number of cognitively based recommendations and even some related human factors research, very few empirical studies have directly tested these recommendations. For the most part the research emphasis has been either on the description of mental models for particular kinds of tasks (Alexandridis, Entin, Wohl, & Deckert, 1984; Govindaraj, Poturalski, Vikmanis, & Ward, 1981; Posner & McLeod, 1982; Wohl, Alexandridis, Entin, Deckert, & Lougee, 1984) or on cognitive task analysis (Bachert, Evers, & Santucci, 1981; Crolotte & Saleh, 1979, 1980).

One line of research has identified and empirically validated six salient formatting parameters in several task settings (Tullis, 1981, 1983, 1984; Schwartz, 1986), and another has tested principles from Rasmussen's cognitive-processing model in a nuclear power plant setting (Pew, Miller, & Fechner, 1981), but such endeavors are still relatively rare. Consequently, the present report constitutes the first phase of a research program aimed at identifying and testing the utility of cognitively derived display concepts. It is based on a selective review of literatures on C3I type tasks, display principles, and human information processing functions, with an eye toward identifying promising variables (or concepts) for evaluation in a simulated system context.

Purpose and Organization of the Report

In view of its limited and focused objectives, the report does not represent a comprehensive review of display, task, or cognitive research. Rather, it concentrates on those display concepts which, on the one hand, basic research suggests should make a difference in some aspect of human cognitive performance, and on the other, are logically related to task demands that commonly exist in C3I systems. It is not intended as a handbook for system designers, for indeed several excellent references summarizing our collective present knowledge on human factors in display design already exist (Engel & Granda, 1975; Sidorsky, Parrish, Gates, & Munger, 1984; Smith, 1980; Smith & Aucella, 1983; Smith & Mosier, 1980; Woodson, 1981). Neither is it a taxonomic analysis of C3I systems, for that, too, has been done (AFAMRL/HEC, 1980, 1981; Crolotte & Saleh, 1979, Sage, 1981; Systems Research Laboratory, 1985; Wohl, 1981). Rather, it attempts to lay groundwork for the research that will add sections to those handbooks or make more explicit the implications of certain display concepts that are already included. The emphasis is exclusively on cognitive process implications of display.

The remainder of the report is organized into two sections. The first discusses various features of C3I tasks and the particular cognitive requirements that each poses for the operator. The second explores several cognitive research domains that bear on these requirements.

Task Characteristics

Demands and Constraints

A review of descriptive material on a variety of C3I systems and laboratory analogs of such systems reveals that while there are broad functional similarities, the tasks facing the operator vary considerably over systems (AFAMRL/HEC, 1980, 1981; Alexandridis et al., 1984; Alphascience, 1984; Crolotte & Saleh, 1979; Department of the Army PATRIOT, 1983, 1984a, 1984b; Harris et al., 1985; Marvin et al., 1985; Noble & Truelove, 1985; Pearl, Leal, & Saleh, 1980; Systems Research Laboratory, 1985; Wohl, 1981; Wohl et al., 1984). Using Rasmussen's (1983) classification they range from the highly structured *rule-based* kind to the more open-ended *knowledge-based* variety. Fewer would seem to fall under his definition of *skill-based* tasks, although it is possible that some become fairly "automatic" in the sense of placing few demands on mental resources. In some cases, such as the PATRIOT system (Department of the Army PATRIOT, 1983, 1984a, 1984b), requirements vary from rule-based to knowledge-based within the same system depending on which mode it is in. Others, such as the (V(INT)2) concept (Harris, Fuller, Dyck, & Rogers, 1985; Marvin et al., 1985) involve a continuing interplay between user and automated functions, thereby incorporating knowledge and rule-based demands within the same task scenario.

Most military C3I systems perform some combination of information gathering, diagnosis or inference, planning, action selection and communication (including command) functions. To accomplish these broad objectives, they may carry out a host of more specific functions such as resource allocation, threat evaluation, monitoring, scheduling, tracking, forecasting, etc. and do so under a wide array of configurations and constraints. The most universal constraints are *time*, *uncertainty*, and *valued* *resources* (personnel and materiel). Frequently there are trade-offs among these constraints: time and resources can be used to "buy" information and thereby reduce uncertainty. Time becomes more critical as uncertainty increases; sufficient resources can offset deficiencies in the other areas; low uncertainty permits greater use of efficient rule-based operation; etc. The operator's role, therefore, can vary substantially in terms of primary *function* performed as well as nature of the constraints even within the same system or problem over time.

Rule-based Cognitive Functions

To the extent that a specific task is more rule-based than knowledge-based, whatever its purpose in the overall mission of the system, the critical aspect of the operator's performance becomes increasingly that of mere compliance with those rules. From a cognitive standpoint, this usually calls for fairly "low level" processing such as *detecting*, *locating*, *identifying*, or *comparing* displayed information, and making predetermined responses based on those processes. Since there are clearly defined (by the rules) criteria for appropriate behavior, *accuracy* is a meaningful performance index; speed or timing may also be of vital importance. Inaccuracy (errors) may take several forms (*omission*, *commission*, *perceptual*, *response*), and speed-accuracy trade-off functions may assume some importance.

It goes without saying that rule-based tasks are the easiest to automate, but for reasons discussed earlier, they still merit our attention. Moreover, their well-defined nature makes human performance research particularly tractable: one can design studies to pinpoint how human performance deviates from optimal under various display and task conditions, and one can proceed from either a theory-driven or practical (system-specific) orientation.

Saying that rule-based tasks primarily involve "low level" processing is to an extent misleading. It does not mean that they are necessarily simple; neither does it imply that we fully understand the cognitive processes involved (Johnston & Dark, 1986; Posner & McLeod, 1982). It means only that the required operations are clearly defined and the human contribution tends to be more perceptual or "front-end" than conceptual or creative. The "states of nature" (i.e., stimulus sets, response sets, and linkages) are all well articulated. But it is well established that even the most straightforward perceptual task calls upon a wide array of cognitive processes (e.g., feature analysis, filtering, integration, short-term and long-term memory) that are "driven" both by external stimuli and internal control processes. Some processes are believed to be costly in terms of mental capacity or attentive effort; others are less demanding—perhaps even "automatic." Some seem capable of being carried out in parallel; others occur serially. Some combinations seem to interfere with one another seriously; others do not. All of these characteristics have a bearing on the extent to which human performance conforms to the specified rules and optimal models. Each process has the potential for contributing error and/or delay to the final task "product."

In view of the fact that they are at least partly stimulus driven, such processes have particular relevance for the area of display design. While we are far from understanding them completely, as noted above, the body of empirical knowledge and plausible theory has grown substantially in recent years. One can identify display and task conditions that should produce certain kinds of processing (e.g., parallel vs. serial) or certain kinds of errors (and/or delays) in processing (e.g., confusions). Yet few studies have attempted actually to test these generalizations in the context of either specific or generic C3I systems. Consequently, the bulk of the second section of this report focuses on "front-end" processes--primarily those included under the headings of attention and perception--that are particularly germane to rule-based tasks of the sort encountered so frequently in C3I systems.

Knowledge-based Cognitive Functions

Virtually all systems also have some conditions under which the operator is called upon to perform knowledge-based functions. Such tasks include fault diagnosis, threat evaluation, various kinds of estimates and predictions, inferences and diagnoses, mental calculations, and choices. They may involve risk, uncertainty, and utility considerations; application of logic or "intuition"; or use of principles and databases stored in the individual's long term memory. Collectively they may be said to require judgment, problem-solving, and conceptual skills—some kind of manipulation of perceived information rather than simply translation into a prescribed response. They vary in level of abstraction and hence kind of understanding required of the operator (Rasmussen & Lind, 1981; Rasmussen, 1984).

For such task requirements, correct or optimal performance is not always easily specified. Neither are the cognitive operations that underlie performance. Therefore, rather than using indexes such as *accuracy* or *latency*, performance is frequently evaluated relative to some model of either optimal or typical processing functions. For example, "policy capturing," "clustering" and "process tracing" or "protocol analysis" methodologies are commonly used to infer how an individual goes about evaluating and using items of predictive or diagnostic information in arriving at a set of judgments, decisions or solutions. Bayes theorem is often used as a reference for human diagnostic performance. Rational models (expected value, expected utility, subjective expected utility maximization) constitute the criteria against which human choice decisions are judged. In each case, however, the model itself rests on certain important assumptions (e.g., that the predictive system is linear; that people can express their thought processes accurately; that people aggregate information in a more-or-less Bayesian fashion; that one can define rationality; etc.). In other words, how—and how well—an operator or system is performing these "higher level" (more conceptual, knowledge-based) tasks can rarely be specified in straightforward, unambiguous terms. One generally attempts to identify an aspect of the overall cognitive function that is *logically* related to system performance (and is more or less measurable), and tests human performance against that aspect. For example, if a display variable alters the weighting strategy that an operator uses in aggregating a set of predictive items (as some recent research has suggested), we assume that is worthy of consideration in the design of displays because it will affect ultimate system decisions. Be we cannot specify *which* design is preferable until we know the "true" cue-criterion relationships for a particular system.

One would not expect display variables to have as much impact on the performance of these conceptual tasks as on those involving the simple *extraction* and *interpretation* of information (where the response is dictated by rules once the "front-end" processes are completed). Evidence on this point, however, is mixed. Displays that preserve critical spatial relations clearly help in fault diagnosis tasks (Wickens, 1984). Similarly, judgment tasks that involve integration of several dimensional values (e.g., length and width) are enhanced by displays that provide the integral concept (e.g., area) directly rather than separately (Wickens & Vidulich, 1982). A growing body of research in our own laboratory supports the notion, originally put forth by Hammond (1986), that graphic encoding encourages "holistic" processing whereas alphanumeric encoding encourages a more "serial" approach (Kerkar & Howell, 1984). This difference has been observed in a variety of conceptual tasks, particularly where some form of stress is involved (Kerkar & Howell, 1984; Schwartz & Howell, 1985). On the other hand, some studies (e.g., Schwartz, 1986) have suggested that such display effects operate mainly on the front-end processes, and any overall advantage derives from more *complete* extraction of information or more *efficient* extraction (which, in time-constrained tasks, would leave more time for conceptual processing). Others simply have not found substantial display effects (Anderson, 1977; Goldsmith & Schvaneveldt, 1981; Knox & Hoffman, 1962).

It is here, of course, that the approach of trying to identify descriptive *mental models*, generating testable display design hypotheses from them, and then conducting the tests in a realistic (specific) system context makes the most sense. Given the complexity of the cognitive processes involved, their relative inaccessibility, and the fact that they are preceded by various other cognitive processes, it is difficult to pinpoint the locus of any observed effects, and hence generalize to other system contexts. Still, any obtained display effects would be of practical value for the system in which they were observed, and would constitute hypotheses for test in other contexts. For purposes of the present report, the message is that easily generalized display concepts are more likely to be found in the domain of information extraction and interpretation processes than in that of the higher-level conceptual processes. For this reason, the emphasis in the next section is on such processes.

Theory and Research on Selected Cognitive Functions

Information Extraction and Interpretation

Review of the current literature on "front end" processes from the standpoint of display design possibilities identified four areas of particular interest. The first centers around the widely accepted notion that man has a limited capacity of mental (or attentional) resource to apply to the task at hand at any given moment. A major threat to information extraction and interpretation in C3I tasks is the momentary deficiency in capacity available for processing particular items on the display. Such deficiency, which can produce confusions, errors, and delays, may arise for several reasons including the coincidence of key information to be processed (time-sharing requirement), the presence of irrelevant information that interferes with the processing of key information, and the presence of stressful conditions. Each of these sources of difficulty is examined carefully in the following subsections. Since it is also recognized that some processing can take place concurrently (in parallel) rather than serially, and that parallel processing is virtually free from resource capacity limitations, a subsection is devoted to the conditions under which parallel processing occurs.

Mental Capacity Limitations and Time-sharing

One of the salient characteristics of computer display terminals and systems is that operators are often forced to direct their attention to several different things at once. The term "time-sharing" is used to denote situations in which an operator is required to attend to several tasks that are performed in parallel. For example, the system operator might be required to track several possible targets while simultaneously receiving voice input, issuing verbal commands to other personnel, and manually operating various switches that control the characteristics of the display hardware. Similarly, display screens can be broken into several logical regions. In the case of C3I system displays, one portion of the screen may be devoted to presenting targets while another portion may contain status information or explanatory codes. The recent proliferation of computer visual interfaces that display information from concurrent processes in multiple active display "windows" provides another example of this type of time-sharing requirement.

In view of the prevalence of tasks that require operators to divide their attention among several ongoing functions, the development of theories to predict and explain human performance in time-sharing situations is of considerable practical importance. This section summarizes both traditional finite-capacity models of human information processing as well as recent alternative views that stress operator skill and practice as the determinants of multiple-task performance. Implications of these theories for the design of computer displays are also discussed.

Traditional views of divided attention (the finite-capacity approach). Traditional views of the divided attention situation have been based on the position that conscious attention can be focused on only one task at a time. Thus, multiple task performance is achieved by switching rapidly from one task to another (Broadbent, 1958). Theories of divided attention have differed in their views of the underlying nature of what is shared among tasks; however, they are similar in that they can be seen to characterize processing capability in terms of a resource metaphor (Moray, 1967; Navon & Gopher, 1979; Norman & Bobrow, 1975).

In the single resource view of divided attention, the basic idea is that a finite "pool" of mental processing capacity exists in each operator. Much like the processing overhead associated with multitasking computer operating systems, performing several tasks concurrently is predicted to have an unavoidable and negative impact on the level of performance of each task relative to its single-task level (Moray, 1967; Navon & Gopher, 1979). Here, performance is seen to be slowed by both the fact that (a) multiple tasks are competing for the same resources and (b) the act of switching attention between tasks itself consumes additional processing resources beyond those needed for the component tasks.

Several factors have been advanced to determine the extent to which multiple task performance will degrade the level of performance of the component tasks; of these, task similarity and difficulty are the most important (Kerr, 1973; Wickens, 1984). In terms of similarity, performance will be diminished more when the tasks make similar information processing demands (e.g., encoding, rehearsal, transformations) on the operator (Kerr, 1973). A means for quantitatively expressing the level and cost of time-shared performance in terms of a performance resource function (PRF) was developed by Norman and Bobrow (1975).

Additionally, task difficulty is predicted to have a relatively straightforward effect on performance: the more difficult the task, the greater the cost of concurrent processing (Wickens, 1984). Research on the single-resource approach has generally supported these predictions (e.g., Gopher & Navon, 1980; Moray, 1960; Neisser & Becklen, 1975; Schneider & Fisk, 1982; Stevenson, 1976; Treisman & Geffen, 1967; Wickens & Gopher, 1977).

Unfortunately, the single resource models have been unable to explain a number of other findings, including failures of task difficulty to influence performance (e.g., Wickens, 1976) as well as cases in which there is no apparent cost of time-sharing (e.g., Allport, Antonis, & Reynolds, 1972). To explain these and other findings, the single resource model was broadened to incorporate multiple processing resources (e.g., McLeod, 1977; Navon & Gopher, 1979).

The basic difference between the single- and multiple-resource views is that the latter organizes processing capacity into several different resource pools. Wickens (1984) maintained that these resources vary on three basic characteristics or dimensions: *stages* (early vs. late processing), *modality* (auditory vs. visual encoding), and *processing code* (spatial vs. verbal). As before, the costs of concurrency will vary as a function of the specific resources required by each task: for example, decrements in time-sharing performance should be greater to the extent that the tasks demand common resources.

Alternate views of time-sharing performance. A limitation of all of the approaches discussed above in explaining time-sharing performance is that they focus on only the characteristics of, and interrelationships among, the tasks that are to be performed and largely ignore the role of learning or unique characteristics/abilities of the individuals who perform the tasks. An entirely different view of the dynamics of human performance in divided attention/time-sharing tasks that acknowledges the role of such variables has been taken. This conceptualization rejects the view that only a finite amount of information processing "capacity" exists in favor of a representation of task performance that is limited only by the subject's willingness to practice the different skills to be performed simultaneously.

Several studies have reported results that appear to contradict the position that there is only a limited amount of processing ability and that multiple-task performance must invariably be inferior to corresponding single-task levels. In an experiment in which operators alternated between a single- and a double-task setting, Damos and Wickens (1980) found evidence suggesting that practice in the dual-task condition led to the development of a time-sharing skill that generalized to other tasks. Similarly, Damos (1978) found that flight instructors performed better in a dual-task setting that involved a flight task than did less well-trained individuals, presumably due to the flight instructors' high level of skill at the flight task.

Neisser and colleagues (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Spelke, Hirst, & Neisser, 1976) employed tasks in which subjects received high levels of practice. Spelke et al. (1976) had subjects practice for weeks on a task that involved writing dictation while reading other material for comprehension at normal speed. After extensive practice, their results indicated that reading and writing were performed as effectively apart as simultaneously; Spelke et al. concluded that attention is best viewed as a skill that improves with practice. Hirst et al. (1980) performed a follow-up study designed to test competing explanations of the Spelke et al. (1976) results: namely, that attention could be alternated very quickly between tasks (i.e., without a measurable performance decrement), and that one of the tasks had become "automatic" and thus posed no demands that could interfere with the other. Hirst et al. found that subjects (a) were able to transfer previously acquired time-sharing performance levels to a new time-sharing task, thereby supporting the position that the performance reflected an acquired skill; and (b) recalled and integrated information obtained from a copying task performed while simultaneously reading other material, thereby ruling out an automaticity argument. Neisser and colleagues concluded that prior limited-capacity research guidelines may be applicable to performance of relatively unskilled tasks but inappropriate for explaining the performance of individuals who are practiced at the tasks.

Evidence suggesting that time-sharing performance may be partly determined by individual differences in an ability to time-share has also been reported. For example, although subjects in the Spelke et al. (1976) experiment were equally successful in time-sharing, some of Hirst et al.'s (1980) subjects were unable to immediately transfer their previously acquired time-sharing skill to a new task; this suggests that meaningful individual differences existed between subjects.

Similar conclusions may be drawn from the results of studies measuring individual differences in flexibility of switching attention in a dichotic listening task (Gopher, 1982; Gopher & Kahneman, 1971). In this research, measures of attention flexibility were found to be valid predictors of flight training success and accidents. To what extent such differences reflect underlying differences in a "time-sharing ability" has yet to be determined.

The research on highly practiced task performance calls into question the implications of the finite-capacity theories of divided attention. In particular, findings based on the use of relatively unpracticed subjects may seriously underestimate the levels of performance that are possible with extensive practice (Spelke et al., 1976). Given that the operators of many, if not most, military computer displays will have been carefully selected and highly trained in the tasks to be performed, the display and task structuring guidelines derived from traditional theories of divided attention may provide only a lower bound to the level of performance that is possible.

Additionally, evidence suggesting that individuals may differ in their ability to successfully time-share raises the possibility of optimizing operator performance by selecting trainees on the basis of their scores on such abilities. However, we currently lack both the ability to assess such differences as well as evidence that a true general ability to time-share (that is independent of the specific task to be performed) exists.

Practical and research implications. Clearly, one cannot assume that capacity limitations will operate to degrade performance under all multiple-task, complex-display situations such as are typical of C3I systems. For one thing, the multiple-store notion suggests partial independence of resources, and at least an initial hypothesis as to the differentiating properties. This concept merits close attention in the context of C3I tasks. For one thing, some processing can apparently take place in parallel (i.e., without time-sharing), and perhaps training and/or individual differences partially control the range of tasks that fall within this category. To what extent, insofar as C3I tasks are concerned, remains to be determined.

In the remaining subsections, emphasis is directed to those cognitive task requirements that seem particularly conducive to interference, on the one hand,

and parallel processing on the other, recognizing that training and selection are alternatives to display design that merit consideration in their own right.

Irrelevant Information Effects

Advances in computer technology have afforded display designers the "luxury" of using numerous design enhancements such as color, graphics and windowing to create "optimal displays." Unfortunately there has been a tendency to overuse these capabilities. The result, as noted earlier, is displays which may be cluttered, disorganized and full of competing information (Wiener, 1985). In order to avoid this kind of over-application of technical capabilities, we must be aware of the cognitive limitations of the display user. The purpose of the present section is to explore the ways in which irrelevant information can operate to lower human performance.

It is well documented in the literature that the presence of irrelevant stimuli in a display can interfere with the relevant task. This has been found to be true for a multitude of task situations including search/detection tasks (Kahneman & Henik, 1981), reading tasks (Treisman, Kahneman, & Burkell, 1983) and Stroop tasks (Stroop, 1935; Dyer, 1973). The hypothesized causes of interference in these tasks can be broadly grouped into three categories (Treisman, Kahneman & Burkell, 1983): confusability of the irrelevant item and the target, evocation of a conflicting response by the irrelevant stimulus, and competition between perceptual objects for attention (see section on mental capacity limitation and time-sharing above).

Confusability. One can picture many examples of displays in which irrelevant information is very similar in appearance to relevant information. Very often display users are asked to search for a particular kind of alphanumeric information in a display which presents many different kinds of alphanumeric information. Consider an inventory task in which the user is asked to find an item designation in a string of numbers representing site location as well as item identification. Will the additional characters representing location interfere with the search for and detection of the item number? A number of studies have addressed this general issue and identified several variables that determine how much interference is likely.

Kahneman and Henik (1977) had subjects look at a string of 12 consonants for 200 msec and report as many blue consonants as possible. Several variations of the display were presented, and displays consisted of either red and blue letters or blue letters and spaces (in place of the red letters). Configuration of the display was either two six character lines in monochrome, two lines each containing two groups of three monochrome characters, or a checkerboard arrangement in which the colors of characters alternated. Results showed that the display of target letters with spaces was superior to that of red and blue letters. In other words, the distracters did cause interference in this task because they, like the target stimuli, were letters. Since spatial location was controlled (i.e., all letters occupied positions the same distance from one another) the results cannot be attributed to spatial coding.

In a similar experiment, Estes (1972) asked subjects to detect a letter target in a display which was presented for a brief period of time. When the display was an array of letters, subjects made significantly more detection errors and responded slower than when the distracters were small matrices of dots. As long as the distracters were not confusable (in the sense of generating errors), the decision latency was not affected by the number of distracters present. However, increases in the number of characters in the all-letter displays produced increases in both errors and latencies.

Turning again to the Kahneman and Henik (1977) study, another variable that affected interference was display configuration. When the blue and red letters were grouped separately in a line or in groups of three, the interference was small but significant. In contrast, the checkerboard arrangement provided for the greatest degree of interference. It appears, therefore, that interference increased with the number of perceptual units or groups: hence another factor to be considered is that of perceptual grouping.

As summarized by Wertheimer (1958), the Gestalt principles of organization included proximity, similarity, common fate, good continuation, closure, area, and symmetry. Of these, proximity, similarity and closure have proven most important in the design of visual displays. The principle of proximity states that grouping of individual elements occurs on the basis of spatial contiguity. The principle of similarity states that elements which are physically similar will be perceived as belonging together. The principle of closure states that, if possible, objects will be perceived as simple closed figures instead of incomplete ones. From a practical standpoint, these principles suggest a variety of coding strategies and problems. Typically, of course, one attempts to designate common elements or events on a complex display by a common feature, such as a color or shape which is clearly differentiated from other colors or shapes. In so doing, however, one encourages *grouping of* those elements, which may enhance or degrade performance depending on task objectives. If the pattern itself provides useful information, grouping would be expected to help; if the pattern is irrelevant, or the focus should be on individual elements, grouping could hurt performance since it may be difficult or impossible to ignore (see below).

Perceptual grouping is most commonly achieved by manipulating shape, color or other physical properties, as well as spatial distance. Spatial distance or location may actually differ from other features in terms of perceptual processing. There is evidence that locations are registered earlier than other aspects of the visual field (Kubovy, 1981). In reference to Kahneman and Henik's (1977) results, even though color distinguished the relevant and irrelevant items, the checkerboard arrangement so dispersed the colors that they were not seen as a perceptual group, but rather as many perceptual groups having one member each. In contrast, when the items were grouped in three's according to color, perceptual grouping was achieved and less interference was experienced. Several other perceptual grouping experiments also have implications for the problem of display design.

Kahneman and Henik (1981) again had subjects search a string of letters, this time for a two-letter target. The characters were mixtures of red and blue. When the target pair was monochrome, detection rate was significantly higher than when the target pair was multi-colored. The same effect occurred for targets that were letter/digit pairs: homogeneous pairs were detected significantly better than heterogeneous pairs. The robustness of the effect of perceptual grouping can be seen in the somewhat surprising results of Banks, Bodinger and Illige (1974). They found that increasing the number of distracters in a search display actually *improves* performance if it improves the grouping of the distracters.

Even attributes as basic as line orientation have been found to show the perceptual-grouping effect. Beck (1966), for example, asked subjects to rate similarity of simple two-line elements (L,T,+,V,X) in various orientations. Subjects rated elements "similar" if they were identical except for orientation. The subjects were then shown a display where three different stimuli were each represented as a large group. The three large groups were displayed next to each other with no gaps (contiguous arrangement). When subjects were asked to divide the field into two areas where the break would most naturally occur, they grouped 90 degree angles together against the 45 degree stimuli.

A final example of the benefits of perceptual grouping for a display set prone to interference concerns the visual suffix effect. Kahneman and Henik (1981) showed subjects a string of digits for 200 msec for recall. Some trials had suffixes of various types (including "O", "A" and several conjunctive characters) tagged onto the end of the string. Once again, it is relatively easy to picture a situation in which strings of characters to be searched could have irrelevant characters added to the end of the strings. Kahneman and Henik (1981) found interference with almost every suffix. Because the suffixes were similar to digits and spatially separate from the target, the suffix interfered with recall of the other items. The suffixes which did not cause interference were those perceptually segregated from the relevant items as illustrated below:

```
     0
     0
123450
     0
     0
```

To complete the discussion of perceptual grouping, it is necessary to consider briefly the model of visual search proposed by Treisman and Gelade (1980), which is currently enjoying wide acclaim. Current theories of perception agree that perceptual grouping occurs automatically, in parallel without attention. Whenever targets are defined *disjunctively* (i.e., "search for a blue target OR an S"), the search can proceed in parallel. If targets are defined *conjunctively* (i.e., "search for a blue S"), the search must proceed serially, focusing attention on each item in turn (Treisman & Gelade, 1980). In other words, elements differing in color or shape are easily segregated into their groups. In contrast, elements which are conjunctions of colors and shapes are not easily segregated, and in fact require a search that is serial rather than parallel. When perceptual grouping occurs, the search between groups is serial and the search within groups is parallel. When the structure of the display allows attention to be spread over several homogeneous groups, there is no risk of illusory targets (accidental conjunctions) so the features within the groups are searched in parallel (Treisman, 1982). One more interesting finding is that conjunctive targets are somehow camouflaged when they are placed on a boundary between two groups that share one dimension each with the conjunctive item. This effect is does not occur for nonconjunctive targets (Treisman, 1982).

Conjunction errors have even been found to occur with higher level codes than features. Virzi and Egeth (1984) had subjects view an array of digits for later recall. During the retention interval, subjects were shown either a neutral word or a word that was a color name word printed in either a congruent or incongruent ink color. At the end of the display, subjects were asked to recall the word presented, the ink color in which the word was presented, and the digits from the first display. The most surprising result was that subjects reported color-name words when in fact, the color was presented only as the ink color. The result is explained as an illusory conjunction of the color-name word and the ink color.

After considering the above results, it is relatively easy to picture the kinds of real world display situations that should be susceptible to interference due to confusability of stimuli. For example, alphanumeric displays typical of C3I systems contain columns and rows of coded, abbreviated, or otherwise cryptic information with differences between two critical designations being a matter of no more than two or three letters.

Conflicting responses. The second type of interference occurs when irrelevant stimuli evoke responses which are in conflict with responses evoked by the relevant stimulus. The most well-known example of this is the Stroop effect. Stroop (1935) found that when subjects are asked to name the color of ink in which an incompatible color-name work is printed, there is a significant delay relative to naming the color of ink in which a non-color-name word is printed. This effect has been investigated by numerous researchers (see reviews by Dyer, 1973; Jensen & Rohwer, 1966) and has a remarkable resistance to practice effects. It is thus one of the best documented failures of selective attention (Kahneman & Henik, 1981). Several theories have been advanced to explain the Stroop effect, and among the most successful in terms of research support is the response competition theory.

Keele (1972) maintains that the Stroop task is basically a selective attention task. Since selective attention must operate after memory retrieval, it is only when different responses are elicited that the response competition occurs. One experiment supporting this theory used color names (e.g., "aqua") for the Stroop stimuli that were less common than those typically employed (e.g., "blue") and found less interference. Since degree of familiarity involves meaning, interference could have only occurred after memory retrieval in the response stage (Langlois, 1974). Further, Wheeler (1977) and Redding and Gerjets (1977) found that reaction time delays for verbal responses did not manifest themselves when finger responses were used. Thus, a change in type of response (i.e., verbal to manual) results in a change in level of interference. (We should note, however, that interference is not always eliminated with a manual response as shown in a study by Compton and Flowers cited below.)

One of the most supportive pieces of evidence for the response competition theory are the results of Duncan-Johnson (1981). She employed the P300 component of the event-related brain potential which is used to determine at what stage cognitive events are occurring. The measure is recorded from the scalp as a positive voltage with a latency of 300 msec following a cognitive event. The latency of P300 has been shown to vary systematically with the requirements for evaluating a stimulus (Polich, Vanasse, & Donchin, 1981). Tasks requiring response selection affect reaction time but do not affect P300 measures. Thus, P300 can serve as an index of the duration of stimulus evaluation processes, independent of response production (McCarthy & Donchin, 1980). Duncan-Johnson (1981) found that the P300 values were approximately the same for control and incongruent conditions of the Stroop task, suggesting that it is in response selection rather than in stimulus processing that the interference occurs.

The Stroop effect is so robust, in fact, that the color and color-name word need not be integrated in order to cause interference. Dyer (1973) showed subjects a vertical color strip with a color name on either side. As in the traditional Stroop task, interference was found when the color strip was incompatible with the color name word. Kahneman and Henik (1981) showed subjects a pair of words, one in black and one in color. In half of the trials the entire word was in color; in the other half only one letter was in color. Results showed that in the absence of conflict, the color naming task is easier if the entire word is colored rather than one letter. When there was conflict, the word that was entirely colored caused more conflict. Even when only one letter was colored, considerable delays in naming the color were found. Keep in mind that unlike the traditional Stroop task where the word stimulus is associated with an incompatible response, no incompatible response was associated with a particular letter in this study; thus it appears that attention cannot be focused on the relevant object.

Compton and Flowers (1977) found a Stroop-like effect for dimensions other than color. Subjects were shown a consecutive presentation of an achromatic shade word name and an achromatic shade patch. Shades used were gray and black. Shade names were printed in white on either a black or gray background. Subjects were to press a key signifying whether the shade name presented matched the shade patch presented. A significant delay in response time was found when the background shade and shade name differed. In another experiment (Compton & Flowers, 1977), subjects were asked to match a shape name presented inside of a shape, where the shape was sometimes incongruent (i.e., "circle" printed inside of a square). Again, consecutive presentation was used and subjects had considerable difficulty when the shape name and shape were incongruent. Similar results have been found when the stimuli were incongruent typeface and typeface name (i.e., "bold" printed in script) (Warren & Lasher, 1974).

As noted earlier, location seems to play an important part in determining level of interference of irrelevant stimuli. Gatti and Egeth (1978) conducted a Stroop experiment where color patch and color name word were spatially separated. They found that interference from an incompatible color name decreased from 90 msec at 1 degree distance from the color patch to 40 msec at 5 degrees. In this instance, not only do the stimuli provide conflicting information, but because they are spatially separate, there could be an added effect of division of attention/resources.

Perceptual competition. The final category of factors associated with interference from irrelevant stimuli involves the diversion of attentional resources away from the target by the irrelevant stimuli. Eriksen and Hoffman (1972) found a consistent delay in naming a single letter when irrelevant objects were added to the display. These objects were in no way confusable with the letter, and were in fact black disks or color patches. The same effects were found by Treisman, Kahneman and Burkell (1983) and Kahneman, Treisman and Burkell (1983). Because Kahneman and his colleagues found that delays could be eliminated by precuing the location of the word, the effect of delay was termed "filtering cost." This concept differs from that of interference caused from conflicting responses and confusable stimuli (discussed above) in that the delay is seen as a result of attention allocation and the filtering out of irrelevant objects. Thus, filtering costs occur even with highly discriminable stimuli. The concept of filtering costs is based on the suggestion (Kahneman, 1973; Treisman, 1969) that the allocation of attention to an object facilitates proccessing of all parts of the object, relevant and irrelevant. It may be useful to examine the specifics of several of these experiments.

Treisman, Kahneman and Burkell (1983) had subjects read a display which contained either a word, a word alongside a shaded shape, or a word inside of a shaded shape. Here, the colored shape is not confusable with the target word and does not evoke a competing response. Nevertheless, results show that the presence of the shape causes a substantial delay in reading. The interesting finding is that the delay is reduced by one-half when the word is displayed inside of the shape. It appears that the interference occurs when two separate objects are present because both objects compete for attentional resources (see section on mental capacity limitations and time-sharing above). In fact, according to the assumptions of filtering costs, both the shape and word should benefit from being presented together because when attention is allocated to an object, the processing of all parts of the object is enhanced. A second experiment involving a dual-task situation shows this to be true. Treisman and her associates (1983) had subjects read a word in displays identical to those used in the experiment just described. The secondary task, however, was the identification of the location of a small gap in the outline of the shape. Subjects performed better on both the primary and secondary tasks when they were integrated (i.e., word in shape). Apparently, dividing attention between parts of the same object is easier than dividing attention between two separate objects.

Comparing these results with findings discussed in previous subsections, it appears that spatial segregation guards against interference due to confusability or conflicting responses, but is actually detrimental if it sets up a conflict for attention between objects. What can be done to avoid this situation? Kahneman, Treisman and Burkell (1983) completely eliminated the interference effect of irrelevant objects by precuing the location of the target to be read. They found identical results when the distracters were presented in advance of the target. Similar beneficial effects of precuing have been found by Colgate, Hoffman, and Eriksen (1973), and Eriksen and Hoffman (1972, 1973, 1974).

To summarize, the present review has focused on three primary categories of interference caused by irrelevant stimuli in the visual field. The basic research findings presented here are readily applied to developing testable display hypotheses for study in a simulated C3I context. These include interference due to confusability of stimuli, interference due to the irrelevant stimulus evoking a conflicting response, and the division of attention and resources between two objects in the visual field. Although all findings presented were "basic" research results, they may be extrapolated to testable display hypotheses for study in a simulated C3I context. Three concepts worthy of consideration in dealing with irrelevant information effects are: perceptual grouping, precuing of target location and advance presentation of distracters. All, however, also pose "down-side risks" which must be investigated in a proper context.

Stress and Information Extraction

C3I systems typically operate in an atmosphere of stress, or at least it is in stressful situations that performance becomes most critical. Such stress and the increase in arousal associated with it can be induced by many conditions including the danger or criticality of the task itself, time stress, and stress due to sleep loss. This section of the report reviews research on the effects of stress on cognition with specific emphasis on the extraction of information.

An important hypothesis about the effects of stress on cognition was put forth by Easterbrook (1959). Following Yerkes and Dodson (1908), Easterbrook hypothesized a curvilinear relationship between arousal and performance. According to Easterbrook, increases in arousal result in a restriction in the range of cues that are used in performing a task. At low levels of arousal, performance is poor because selectivity is low, and therefore subjects pay attention to irrelevant cues. As arousal increases, selectivity improves, more cues are utilized, and performance improves. At very high arousal levels, selectivity is so great that some relevant cues are ignored and performance declines. Thus, according to Easterbrook's hypothesis, the greater the level of arousal, the less attention is paid to peripheral cues. The relevance of this hypothesis to extraction of critical information for a C3I display is obvious.

Increases in arousal have been found to be associated with a reduction in the processing of peripheral cues in a variety of types of tasks and using a variety of arousal agents (Bahrick, Fitts, & Rankin, 1952; Bursill, 1958; Callaway & Thompson, 1953; Davis, 1948). However, in these studies it has not always been clear whether arousal resulted in a "shrinkage" of the effective visual field or a focusing of attention towards the most important parts of the display. Cornsweet (1969) using a task in which the most relevant cues were in the periphery found evidence for the latter possibility. Stronger support for the proposition that attention is focused on important parts of a display rather than the center of a display was obtained by Hockey (1970). In this experiment, there was one condition in which signals were more likely to appear in the center of a display and one in which central and peripheral signals were equally likely. Increased arousal (as induced by loud noise) improved responsiveness to central relative to peripheral signals only in the condition in which central signals were more likely. Thus, when the center of the display was not more important (did not contain more information) than the periphery, arousal did not result in a redistribution of attention. Further support for this position was obtained by Bacon (1974) who concluded that arousal narrows the range of stimuli that is processed by impairing the memory traces of signals that originally attract less attention.

Although the research reviewed above gives the impression that arousal has been found to have a consistent effect on performance, it should be pointed out that some research has failed to find any evidence of an effect of arousal on attention (Forster & Grierson, 1978; Loeb & Jones, 1978; Pearson & Lane, 1984). It may be that the effect of arousal on attention is not as robust as once thought and/or that it is dependent on a variety of factors such as task difficulty, cue salience, and the cognitive nature of the task at hand that have yet to be clearly articulated.

If arousal tends to increase the likelihood of attending to the most important or most informative aspect of a display, it is reasonable to suppose that such information would be disproportionately represented in the interpretation and subsequent use of information—even in ultimate decision quality. Although time stress has been shown to reduce the number of dimensions used in arriving at a decision (Wright, 1974), it is not clear whether this results from an increase in the salience of the most important dimension or simply because under time pressure subjects do not have time to process more than one or two dimensions. Payne (1982), in his review of research on decision making, concluded that it has not yet been determined whether or not time pressure changes the salience of information.

The effect of stress on the use of informational dimensions is potentially very important for the design of displays portraying complex information (Howell, Johnston, & Goldstein, 1966). Naturally, the problem is to keep the operator from giving too much weight to the most important dimension at the expense of dimensions that may not be the most important but still convey useful information. Since there is little clear-cut evidence on these questions, we have identified this as an important area for investigation. Of particular interest is the combined effects of display format (graphical or tabular) and stress on dimension weighting. Kerkar and Howell (1984) and Schwartz and Howell (1985) found evidence that graphical formats tend to produce more holistic processing of cues and more even cue utilization. If format and stress both affect the degree to which the most important cue (or cues) get weighted, then a consideration of the combined effects of these variables would seem to be important. It may be that format effects could compensate for stress effects (additively), or there may be an interaction between these variables.

Conditions for Parallel Processing

As noted in previous subsections, a critical issue in the design of displays is the manner in which observers process simultaneously-presented stimuli. If stimuli can be processed in parallel without capacity limitations, then different considerations in display design would be relevant than if capacity is limited and must be divided among stimuli present in the visual field. This subsection of the review summarizes the most important research on the capabilities and limitations of human observers to process visual stimuli in parallel. The conclusion of the review is that Treisman's feature integration theory of attention provides the best account of the data and that this theory has important implications for the design of displays.

Development of the concept of parallel, capacity-free automatic processing. Much of the early research on attention and attentional limitations was based on Broadbent's (1958) filter theory. According to this theory, incoming stimuli are placed unprocessed into a memory buffer and then selected by the filter into the limited capacity system. The filter was said to be capable of selecting only on the basis of low-level stimulus information such as location, color, etc. Stimuli that are not selected into the limited capacity system decay without ever having been processed. Although many findings could be interpreted within this framework, filter theory had difficulty accounting for imperfect selective attention. Specifically, it could not account for cases in which unattended information was processed based on its semantic content since the filter was assumed incapable of selecting on the basis of meaning (Moray, 1959; Treisman, 1960). For example, Treisman (1960) demonstrated that when subjects were asked to repeat a message presented to one ear, words presented to the other ear were occasionally reported if they were semantically related to the attended message. This indicates that some of the unattended information received at lease some semantic processing. Others have shown that even when subjects were not aware of a stimulus presentation, the meaning of the stimulus affects them (MacKay, 1973).

Treisman's filter-attenuation theory (1960) was a modification of filter theory to account for the finding that certain words in an unattended message occasionally break through the selective attention filter. She hypothesized that stimuli not selected by the filter are attenuated rather than filtered out entirely. Thus, stimuli that have special meaning to a person such as his or her name or that fit the semantic context particularly well are perceived because the threshold for perceiving them is low. Even when attenuated, enough information gets through the filter for these stimuli to be recognized. Alternatively, it has been proposed that there are no attentional limitations in perception and that capacity limitations occur only in post-perceptual processing stages such as the decision-making stage (Deutsch & Deutsch, 1963). Although much of the research on attentional effects in perception have used auditory stimuli, this review will focus on visual-perception studies because of their relevance for the displays of primary concern. However, the same theoretical considerations generally apply to both.

Shiffrin and Gardner (1972) in a study based on a previous experiment by Eriksen and Spencer (1969) obtained strong support for the proposition that multiple stimuli in the visual field can be processed in a capacity-free manner. In their experiment, four stimuli were presented briefly at the corners of an imaginary square. In one condition (simultaneous), all four stimuli were presented at the same time whereas in another condition (successive), the stimuli were presented in two phases. First, the two stimuli on one diagonal were presented for the same amount of time that all four stimuli were presented in the simultaneous condition. After a delay of 500 msec to allow subjects to switch their attention, the remaining two stimuli were presented on the other diagonal (again, for the same amount of time that all four stimuli were presented). Thus, in the successive condition, the amount of time to process each stimulus was twice that in the simultaneous condition. Clearly, if subjects processed the stimuli serially rather than in parallel, performance would be much better in the successive than in the simultaneous condition. On the other hand, if four stimuli could be processed in parallel then no difference between the successive and simultaneous conditions would be expected. Shiffrin and Gardner found no difference between the successive and simultaneous conditions thus providing very strong support for the view that perception is parallel and capacity free.

Shiffrin and Gardner's data show that a target stimulus can be distinguished from distracters in parallel. However, Duncan (1980) showed that there is a considerable decrement in performance if two targets have to be detected simultaneously. According to Duncan, stimuli are processed at two levels. Processing at the first level is parallel and does not require capacity. However, a stimulus must be processed at the second level before a response can be made to the stimulus and only one stimulus at a time can be selected from the first level to the second. Moreover, second-level processing is itself a limited-capacity operation. According to this conceptualization, if two target stimuli are presented briefly and simultaneously, then both will be processed at the first level. However, since only one can be selected at a time into the limited-capacity system, it is very likely that one would be selected (and therefore detected) while the other would be missed. To test this conceptualization, Duncan used a variation of the simultaneous/successive paradigm of Shiffrin and Gardner (1972), changed so that more than one target could appear at the same time. Stimuli were presented on either the horizontal or vertical "limbs" of a cross. On a given trial, a target could appear on one of the limbs, on both of the limbs, or not appear at all. Subjects were to indicate the presence or absence of targets in the two limbs separately. On trials in which a target was presented on both limbs, the probability of detecting a target was much greater when there was a concurrent correct rejection (on the other limb) than when there was a concurrent hit. Moreover, there was an advantage of successive over simultaneous presentation when there was a concurrent correct rejection but not when there was a concurrent hit. The finding that it is not the number of stimuli that are presented simultaneously but rather the number that must be detected simultaneously that determines performance is important and supports Duncan's notion that stimuli are selected serially from one processing stage to another.

A key question in Duncan's theory and others that posit the existence of more than one level of processing concerns the factor(s) determining the order in which stimuli are selected from the first to the second level. The priority of selection is particularly important since stimuli not selected are hypothesized to be unable to affect a subject's response even though they have been processed perhaps even semantically at the first level. Shiffrin and Schneider (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) proposed that extended practice can lead to what they call "automatic attention responses." When an automatic attention response is elicited by a stimulus, the stimulus is given priority over other stimuli and is immediately selected into the second level. Thus, the probability of detecting a stimulus that elicits an automatic attention response is not affected by the presence of other stimuli as long as these other stimuli do not themselves elicit automatic attention responses.

Empirical support for this proposition comes from a series of experiments in which the task was to search for from one to four targets in a rapidly-presented sequence of displays containing from one to four stimuli per display. For example, the task might be to determine whether either of the letters "F" or "H" appeared in any of a series of rapidly-presented "frames" each containing four stimuli. In this case, the target set size would be two (because there are two possible targets, "F" and "H") and the frame size would be four (because there are four stimuli presented at a time in each display). Load was defined a the product of the target set size and the frame size. If processing were serial, then performance would be a function of load since load is equal to the total number of comparisons needed to determine whether a target had been presented. Shiffrin and Schneider found that after extensive practice, detection was relatively independent of load. In other words, subjects could search for any of four targets in frames containing four stimuli each almost as well as they could search for a single target in frames containing only one stimulus. Their interpretation was that all stimuli presented are processed in parallel at the first level. However, stimuli that had acquired the ability to produce automatic attention responses were given the highest priority for selection into the limited capacity system and thus could be detected independently of load.

An important finding from Shiffrin and Schneider's studies is that automatic attention responses develop only if target and nontarget stimuli are never interchanged over a large number of trials. When targets and nontargets were interchanged over trials, performance was a linear function of load even after extensive practice. Further, Shiffrin and Schneider demonstrated that the development of automatic attention responses is not simply the overlearning of the distinction between two set of stimuli, the targets and nontargets. This was shown most clearly in Experiment 5 of Shiffrin and Schneider (1977) in which the sets of targets and nontargets were switched after automatic attention responses had developed. If all that was learned was the distinction between the targets and nontargets then this change would not seriously affect performance. In fact, switching the targets and nontargets led to an extreme deterioration of performance. Therefore, there appears to be something very active about the way automatic attention responses result in the selection of a stimulus into the second level of processing.

A critical question about automatic attention responses concerns the basis on which they are elicited. Shiffrin and Schneider hypothesized that even before selection, stimuli are processed quite extensively including being processed for meaning. They further hypothesized that automatic attention responses could be elicited by the results of this extensive processing. In other words, automatic attention responses could be semantically based.

To summarize, the theory and data reviewed so far point to the following conclusions about the processing of simultaneously-presented visual stimuli:

a. There is an initial parallel stage of processing in which multiple stimuli can be processed without interference.

b. Stimuli are processed relatively extensively at this first level including being processed for meaning.

c. Stimuli can only be selected into a second and limited-capacity stage of processing one at a time.

d. If two target stimuli are presented simultaneously then it is likely that only one of them will be selected into the second stage of processing and the other one will be missed even though it had been processed for meaning.

e. Stimuli that have served as targets but never as nontargets for a large number of trials develop the ability to elicit automatic attention responses. These automatic attention responses may be semantically based.

f. When a stimulus elicits an automatic attention response it is selected into the next level of processing immediately, regardless of the number of other stimuli present.

Feature integration and subsequent research. A quite different view of attention and perception called "feature integration theory" was presented by Treisman and Gelade (1980). According to feature integration theory, only basic stimulus features (e.g., color, lines, angles, curves, etc.) are extracted in parallel. These features are assumed to be "freely floating" spatially in that they are not localized with respect to the specific stimulus location from which they were derived. Attention must be focused narrowly on stimulus items in order to conjoin correctly the features of stimuli into unitary objects. Features, however, may be conjoined without focal attention based on context and/or experience, although the possibility of conjunction errors may lead to the perception of "illusory" conjunctions.

Treisman and Gelade (1980) as well as subsequent investigations by Treisman and her colleagues provide considerable data supporting feature integration theory. A good example of the type of evidence presented in Treisman and Gelade (1980) which supports the theory is found in the results of a visual search task. In one condition (conjunction), subjects searched for a target (e.g., "R") whose basic features were also shared individually by the distracters (e.g., "P" and "Q"). These characters were such that the tail on the "Q" could be combined with the "P" to form and "R." The target could be discriminated from distracters only by identifying a conjunction of features rather than a single feature alone. It was predicted that in order to avoid conjunction errors, attention would be focused on individual stimuli in a serial manner. In a second condition (similarity), subjects searched for the same target letter among distracters that were more confusable when considered individually (i.e., "P" and "B"), but for which features could not be incorrectly conjoined to form illusory targets. Because there was no possibility for conjunction errors, it was predicted that some form of nonserial search would be employed. Search times in the conjunction condition were a positive linear function of set size with the positive slope equal to one half the negative slope, results consistent with a serial self-terminating search. Search times in the similarity condition were a positive but negatively accelerated function of set size. Search in this condition was, therefore, at least in part parallel.

A comparison of feature integration theory with the view of attention based on Shiffrin and Duncan's work presented previously reveals some important similarities but also some critical differences. Although both approaches assume considerable parallel processing, the Shiffrin/Duncan view assumes parallel processing of form whereas feature integration theory assumes only parallel processing of individual features. The original finding from Shiffrin and Gardner (1972) of no difference between the successive and simultaneous presentation conditions would seem to be difficult to reconcile with feature integration theory because it does not appear that the discrimination could be made on the basis of the features taken individually. The task was to state whether a "T" or an "F" had been presented among stimuli that were T/F hybrids. These hybrids contained the features of both Ts and Fs which would indicate a possibility of illusory conjunctions. Since, according to feature integration theory, serial processing is required to prevent illusory conjunctions from occurring, a difference between the simultaneous and successive conditions would be expected.

A recent study (Ashby, Martin, & Lane, 1986) included a detailed analysis of the stimuli used by Shiffrin and Gardner and found individual features that may have been used to discriminate the targets. For example, neither the "T" nor any of the hybrid distracters had a feature corresponding to the upper-left hand corner of an "F." Further, the "F" was the only stimulus that appeared asymmetrically located on the mask. Thus, it may have been that subjects decided an "F" had been presented if they noticed either of these distinguishing features of an "F" and that "T" had been presented otherwise. To test this hypothesis, Ashby et al. redid the Shiffrin and Gardner study both with the original stimuli and with a set modified so that no single feature could be used as a valid basis for responding. Shiffrin and Gardner's results were replicated when the original stimuli were used. However, a large difference between successive and simultaneous presentation was found with the modified stimuli. Thus, Shiffrin and Gardner's data seem to be accommodated well by a theory that assumes no capacity limitation on the processing of individual features but a limited capacity to perceive objects based on combinations of these features.

Further support for this interpretation of Shiffrin and Gardner's results can be found in a recent study by Kleiss and Lane (1986). This research used the stimuli Treisman had concluded must be inspected serially in order to avoid illusory conjunctions but with the successive/simultaneous task developed by Shiffrin and Gardner. As in Treisman and Gelade's (1980) study, the task was to detect an "R" with "P" and "Q" distracters (the conjunction condition) or an "R" with "P" and "B" distracters (the similarity condition). Both sets of stimuli were presented in the simultaneous and in the successive presentation conditions. As predicted by feature integration theory, there was a substantially larger false alarm rate under simultaneous than under successive presentation in the conjunction condition but not in the similarity condition. Apparently, the simultaneous condition did not give subjects enough time to inspect the stimuli individually and therefore they were prone to illusory conjunctions in the conjunction condition.

It appears from the research reviewed above that the identification of a target stimulus in a multi-item display cannot be carried out in parallel unless the target is discriminable from the distracters (or other potential targets) on the basis of individual features. However, these data were based on subjects who had had relatively little practice with the tasks (one or two sessions). To have practical implications, the effects of long-term practice need to be considered since most users of displays are highly practiced at the task they perform. Experiment 4 of Kleiss and Lane's article provides some data on this point. Subjects were given 20 sessions of practice (approximately one hour per session) using the same task and conditions as described above. The main finding was that although the difference between the simultaneous and successive conditions declined over approximately the first half of the experiment, there was no tendency for the difference to decline further. Therefore, it appears from this study that even after considerable practice, the presence of distracters in the visual field reduces the probability of detecting a target. However, this conclusion seems to be contradicted by Shiffrin and Schneider's data described previously.

How, then, to reconcile Shiffrin and Schneider's results with the present results and with feature integration theory? Treisman and Gelade (1980) suggested that there may have been a disjunctive set of features that distinguished the target and nontargets used by Shiffrin and Schneider. If this were the case then subjects could make the discrimination without conjoining features but simply by considering the features individually. Although no direct support for this hypothesis was given, the findings of Ashby et al. certainly suggest that subjects can pick up on featural differences that are not obvious on first inspection of the stimuli. Recall that Shiffrin's view has been that stimuli are processed quite extensively even before they are selected and that automatic attention responses have a semantic base (see also Schneider & Fisk, 1984). The idea of a stimulus being selected from others in the visual field on the basis of semantic information is in direct contradiction to feature integration theory and the explanation of Shiffrin and Schneider's data in terms of a disjunctive set of stimuli discriminating the targets from the distracters.

Kleiss and Lane (1984) tested whether automatic attention responses are semantically or featurally based. If an automatic attention response is elicited by a letter, then is it elicited by the name of the letter or by the visual features of the letter? To address this question, Lane and Kleiss chose letters whose upper and lower case versions were not visually similar. Subjects were given extensive training on the task used by Shiffrin and Schneider (1977). After the effect of load was eliminated (this only occurred for some of the subjects, and only those subjects for whom the effect of load was eliminated were included in the analysis), the case of the letters was changed. If automatic attention responses were based on the names of the stimuli, then changing the cases of the stimuli would have little or no effect. On the other hand, if automatic attention responses were based on the visual features of the stimuli, then changing the case of the letters would have a dramatic effect. The results were consistent with the latter possibility: performance deteriorated sharply when letters of the opposite case were used. Thus, the improvement in performance that takes place with practice on this task appears to be featurally rather than semantically based.

Practical and research implications. Although it is far beyond the scope of this review to cover all research bearing on the limits to processing of stimuli in the visual field, the research described here allows one to draw some reasonably firm conclusions about attention and perception. First, if a target can be identified on the basis of features considered individually, then there is essentially no effect of the presence of other stimuli on the detection of the target. On the other hand, if the various features of the target must be combined correctly in order to distinguish the target from other stimuli, then parallel processing is not possible and performance will be affected by the number of stimuli present in the visual field. Moreover, even extensive practice with this type of stimulus will not eliminate the capacity limitations. Second, it is generally not possible to detect two or more targets simultaneously, although this has not been tested with stimuli that can be discriminated on the basis of a single feature.

Although the research reviewed here was conducted more with an eye toward resolving basic issues in perception than providing guidelines for the design of displays, there are several implications of this research for display design. Perhaps the primary implication is that information that needs to be found quickly in a complex display should be represented by a single feature whenever possible. For example, if the threat potential of an object is a joint function of its type and the direction it is heading, then it is probably not optimal to represent these two dimensions individually regardless of how clearly each dimension is represented. Instead, it may be better to map these two dimensions onto a single one of threat and represent a high degree of threat with a stimulus that has some feature unique to it. It appears that almost any simple feature can be learned to be used very effectively if adequate practice is given. Therefore, the problem in display design is not so much finding features that attract attention, for any feature can attract attention, but rather finding ways of collapsing multidimensional stimuli onto one dimension so that individual features can be used to represent complex states of the world. An interesting question concerns how displays of this kind would affect decision making in a complex environment. It might be expected that unpracticed subjects would have a difficult time integrating information from dimensions that already each represent multiple dimensions. On the other hand, the practiced subjects might not only be alerted more quickly to the occurrence of important events due to their being coded in one dimension, but they may be able to handle more information simultaneously if some of it is already condensed in this manner.

"Higher-order" Conceptual Processes

The effect of display variables on tasks involving judgment, decision-making and other clearly conceptual processes has not been studied intensely (Payne, 1982). Hammond (1986) has speculated that certain display features such as graphics, encourage "holistic" processing that is more "intuitive" than "analytic" whereas other features such as alphanumerics or verbal stimuli, do just the opposite. Thus, one would expect better performance using graphic presentation where time pressure is involved, but equal or better performance with alphanumeric presentation where it is not (provided the rule for processing the information is well established). Some evidence in support of this notion has appeared within the last few years. In one study, for example, no differences were found between graphic and alphanumeric displays in an optional stopping decision task under self-pacing conditions, but the graphic mode was generally superior under forced-pacing (Schwartz & Howell, 1985). Similarly, a series of policy capturing experiments showed consistent differences between cue-weighting strategies when the cue values were displayed graphically vs. numerically, and here too the results suggested that the difference was attributable to holistic vs. serial processing (Kerkar & Howell, 1984). And finally, Wickens & Scott (1983) showed that cue weighting was superior under the graphic mode when time was an important consideration.

In addition to these judgment/decision studies, evidence favoring graphic or analog representation of complex events (such as process control) in problem-solving or trouble-shooting tasks has been quite consistent (Wickens, 1984). However, as noted earlier, several investigations reported no display effects for "policy capturing" studies (Anderson, 1977; Goldsmith & Schvaneveldt, 1981; Knox & Hoffman, 1962).

Recent work carried out under the present project has raised some important questions about the way display variables affect performance on knowledge-based tasks when, in fact, they do. Tullis (1983, 1984) identified six measurable format variables that, together, predict quite accurately simple look-up task performance for alphanumeric displays. In attempting to extend these predictions to more complex tasks (e.g., monitoring, process-control, judgment), however, Schwartz (1986) obtained some provocative results. The display variables did, indeed, affect performance as expected and the combinations that produced the best performance were not common to all tasks. But when the variance attributable to simple information extraction operations was partialled out, all the differences vanished. It could well be, in other words, that the main contribution of display features to human performance on high-level conceptual tasks is through their effects on lower-level cognitive processes--notably information extraction and interpretation--rather than on the cognitive manipulation of the information per se. Faster, more complete perception of the existing situation could enhance judgment/decision performance through provision of (a) better information on which to base it, (b) more time and "mental capacity" for application to it, or (c) both. For example, under time pressure the serial processing encouraged by an alphanumeric display would permit only a few "cues" to be absorbed for use in making a prediction or judgment. Graphic display on the other hand, would make more cues available and, even if processed in less detail, could well improve the quality of the overall judgment.

The experimental designs used in the relatively few studies on "higher-order" tasks do not really permit identification of the processing level(s) at which overall performance effect occur. Thus, it would appear prudent to address those display characteristics that are known to affect (or are suspected of affecting) "lower-order" cognitive processes (i.e., see the subsection on information extraction and interpretation above) before considering more speculative "higher order" principles. This is not to suggest that one should ignore the relations between display variables and cognitive task performance: indeed, the present project is founded on the premise that such relations are extremely important in the design of modern C3I systems. Whatever display features are manipulated in subsequent studies will thus be evaluated with respect to lower-order and higher-order components as well as overall system performance. The point is merely that there is no compelling reason to look for esoteric display variables that might affect conceptual processing until the effects mediated by better-understood extraction/interpretation processes are examined more thoroughly in the C3I system context.

Implications for Research: Summary and Conclusions

By their very nature C3I system tasks are immensely complex in terms of information input, display, processing requirements, and response requirements. There is considerable information from a lot of sources that varies over time in important ways. The information must be available in a timely fashion and in a form that maximizes accurate and speedy extraction and interpretation by the human operator, particularly under stressful conditions. It must also be organized in such a way that it enhances--or at least does not seriously inhibit--"higher-order" or more conceptual operations, while at the same time permitting efficient through-put for more routine, rule-based operations. Despite the fact than many of the functions may be automated, and the momentary situation can be greatly simplified from the user's perspective (e.g., by limiting what s/he sees to what s/he needs, whether need is determined automatically or subjectively), there is no escaping the inherent complexity. Just because an operator sees only a selected, highly processed window of information at a particular juncture in a problem does not mean that the rest of the world has vanished or that what s/he is seeing is without history, future, or context. And as long as this is true, researchers and designers can ill afford to ignore basic human information processing principles that might affect the way operators approach this complex set of tasks.

The focus of the present report has been on those processing functions that have the most immediate implications for display design. While recognizing that "higher-level" functions can be seriously affected by the way information is presented, it is not entirely clear that the influence operates directly on those processes; some, if not most, of the effect may come via the more "front-end" processes of information extraction and interpretation. For example, certain predictive "cues" may have a reduced impact on a subsequent judgment because they have fallen victim to "narrowing of attention." Or a conceptual problem may be dealt with effectively because efficient extraction and interpretation left ample time and/or "mental resource" for application to it. Most research to date on display effects has not permitted separate evaluation of "front-end" and "higher-order" influences. Therefore, it seems reasonable to address first those factors that are known to affect attentional (including "resource" or "capacity") and perceptual processes.

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