AD

Technical Memorandum 7-90

INFORMATION PROCESSING AND PERCEPTUAL CHARACTERISTICS OF DISPLAY DESIGN: THE ROLE OF EMERGENT FEATURES AND OBJECTS

Anthony D. Andre
Christopher D. Wickens
University of Illinois

May 1990
AMCMS Code 612716.H700011

Approved for public release;
distribution is unlimited.

U. S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): Technical Memorandum 7-90

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Human Engineering Laboratory

6b. OFFICE SYMBOL (If applicable): SLCHE

6c. ADDRESS (City, State, and ZIP Code): Aberdeen Proving Ground, MD 21005-5001

7a. NAME OF MONITORING ORGANIZATION:

7b. ADDRESS (City, State, and ZIP Code):

8a. NAME OF FUNDING / SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

8c. ADDRESS (City, State, and ZIP Code):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
6.27.16	1L162716AH70		

11. TITLE (Include Security Classification): Information Processing and Perceptual Characteristics of Display Design: The Role of Emergent Features and Objects

12. PERSONAL AUTHOR(S): Andre, Anthony D.; Wickens, Christopher, D. - University of Illinois

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM ______ TO ______

14. DATE OF REPORT (Year, Month, Day): 1990, May

15. PAGE COUNT: 26

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
01	03	
05	08	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): aviation, display, attention, information processing, spatial organization, clutter

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

In this report, the fundamental theoretical and applied principles are outlined, which have been cited to justify the relative benefits of *object displays*, the representation of several quantitative variables as features of single geometric objects. In particular, the proximity compatibility principle is described, which asserts that object displays will facilitate information integration tasks but will disrupt tasks that require focused attention on the individual dimensions of the object. Finally, an experiment is described contrasting three displays: a monochrome object, a multicolor object, and a separated bar graph display.

(see reverse side)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Technical Reports Office

22b. TELEPHONE (Include Area Code): (301) 278-4478

22c. OFFICE SYMBOL: SLCHE-SS-TSB

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

19. (continued)

Subjects were required to either integrate or focus attention on one of three sources of displayed information in an aircraft stall judgment task. Evaluation of the monochrome object revealed superior integration performance but degraded focused attention performance relative to the bar graph display, thus illustrating the proximity compatibility principle. The multicolored object, in contrast, emerged as a display concept that could potentially support accurate integration and focused attention performance, highlighting the role of emergent features and color coding, and suggesting some modifications of the proximity compatibility principle. The results are discussed in terms of their theoretical and practical application to multi-element interface design. (KR)

AMCMS Code 612716.H700011 Technical Memorandum 7-90

INFORMATION PROCESSING AND PERCEPTUAL CHARACTERISTICS OF DISPLAY DESIGN: THE ROLE OF EMERGENT FEATURES AND OBJECTS

Anthony D. Andre
Christopher D. Wickens
University of Illinois

May 1990

APPROVED:
JOHN D. WEISZ
Director
Human Engineering Laboratory

U.S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland 21005-5001

ACKNOWLEDGMENTS

The authors would like to thank Mr. Frank Miller for his programming assistance.

CONTENTS

INFORMATION PROCESSING AND PERCEPTUAL CHARACTERISTICS OF DISPLAY DESIGN: THE ROLE OF EMERGENT FEATURES AND OBJECTS

INTRODUCTION

The display interface for any complex system is a composite of humans and machines organized to attain one or more goals (Adams, 1989). Consequently, determining the most effective display representation relies on an accurate analysis of the operator's cognitive task-processing requirements and of the system properties relevant to the goals of the operator's task (Andre & Wickens, 1989; Carswell & Wickens, 1988; Sanderson, 1986; Vicente & Rasmussen, 1988; Woods & Roth, 1988). To the extent that "goal-relevant" information is present in a display, performance should benefit (Sanderson, 1986).

While the objective of any particular display should be to provide information that is "compatible" with the task requirements of the operator in control, little research existed until recently regarding the optimal display interface between multiple information channels and the appropriate cognitive process (Barnett & Wickens, 1988). As a result, there has been little empirical basis for judging the quality of particular display formats against alternate designs (MacGregor & Slovic, 1986).

As a first step toward assuring compatibility between displayed information and task demands, MacGregor and Slovic (1986) have emphasized the need for developing two taxonomies, the first of which "...would characterize judgment and decision-making responses in terms of their basic cognitive and behavioral properties," while the second "...would describe the essential dimensions along which graphic displays vary and would provide a basis for categorizing display designs in terms of a common set of characteristics," (p.198, ibid.).

A Taxonomy of Cognitive Task Demands

Wickens (Wickens, 1987; Carswell & Wickens, 1988; Andre & Wickens, 1989) has described the general nature of multi-element display processing by identifying three categories of information-processing requirements typical of the kinds of tasks performed in many aviation and process control environments, each representing a different degree to which multiple information channels are uniformly relevant to the goal of a task (Andre & Wickens, 1989). These categories represent requirements for the human operator (1) to *integrate* relevant information sources that together derive the status of an operational property critical to system control; (2) to *divide attention* among those information channels that must be processed in parallel; and (3) to *focus attention* on individual sources of information during "check reading" or fault diagnosis procedures. The present research is concerned with a dichotomous subset of these task information processing requirements, that is, those tasks situated at opposite ends of this continuum of information processing proximity, referred to as information integration and focused attention, respectively (Andre & Wickens, 1989; Carswell & Wickens, 1988).

Although the monitoring or controlling requirements of a speci.ic operational system are not directly reflected by the above-defined taxonomy, the authors are committed to the view that the application of these "macro" or "generic" cognitive task requirements to display design research will lead to a set of theory-based (and therefore generalizable) display design principles. As a testament to this viewpoint, various researchers have used a variety of task scenarios to explicitly represent one or more of the above-defined task information-processing categories (e.g., Andre & Wickens, 1989; Barnett & Wickens, 1988; Beringer & Chrisman, 1987; Carswell & Wickens, 1987; Coury & Purcell, 1988; Goettl, Kramer, & Wickens, 1986; Goldsmith & Schvaneveldt, 1984; Jacob, Egeth, & Bevan, 1976; MacGregor & Slovic, 1986).

A Taxonomy of Display Characteristics

Of course, designing an optimal display interface relies not only on an accurate assessment of the information-processing demands of the tasks to be performed on displayed information, but also on identifying the critical combinations of display variables that will benefit performance. Exactly how to manipulate the perceptual attributes of displayed information in favor of these task requirements is not, however, as well understood (Sanderson et al., 1989).

Although modern advances in display software and hardware technology have enabled system designers to present information in a seemingly unlimited variety of ways (Andre & Wickens, 1989), this design flexibility has not contributed to a consensual taxonomy of critical (performance-related) display characteristics. Instead, these advances have necessitated the development of valid human factors engineering (HFE) design principles that capitalize on human perceptual, pattern recognition, and information-processing abilities to effectively communicate displayed information to the operator (Andre & Wickens, 1989; Mahaffey, Horst, & Munson, 1986; Woods & Roth, 1988).

In this report, the recent theoretical and applied principles are outlined, which have been cited to justify the relative benefits of a novel display alternative, referred to as the *object display*. In particular, the *proximity compatibility principle* is described (Andre & Wickens, 1989; Barnett & Wickens, 1988) which asserts that object displays will facilitate information integration tasks but will disrupt tasks that require focused attention on the individual dimensions of the object; the authors suggest some modifications of this principle based on the theory of emergent features (Pomerantz, 1981) and the recent findings of Carswell (1988). Finally, an experiment is described contrasting three display configurations, two objects and a bar graph, within the context of an aircraft stall judgment task.

It is important to point out that the primary focus of this research is not to promote the advantages or disadvantages of object displays *per se*, but rather to assess the validity and design relevance of the fundamental display principles that have been proposed to support their use. Accordingly, the results are discussed in terms of their support for the applicability of these principles to the evaluation of practical (real world) display format alternatives.

The Object Display

Recent interest in visual display design has been focused on the concept of an object display, that is, the representation of several quantitative variables as features of a single geometric object, rather than as separate bar graphs, meters, or other indicators. Various studies have examined rectangles (Barnett & Wickens, 1988; Cole, 1986), triangles (Carswell &

Wickens, 1987; Sanderson et al., 1989), tetrahedrons (Boulette, Coury, & Bezar, 1987; Goldsmith & Schvaneveldt, 1984), pentagons (Jones & Wickens, in press), or octagons (Woods, Wise, & Hanes, 1981). Such objects have been designed to represent information regarding discrete decisions (Barnett & Wickens, 1988), abstract stimulus classification (Boulette et al., 1987; Goldsmith & Schvaneveldt, 1984), statistical data (Goettl et al., 1986), or energy processes (Carswell & Wickens, 1986, 1987; Jones & Wickens, in press; Sanderson et al., 1989; Woods et al., 1981).

It is not the purpose of this report to review findings of these and other studies, which have reached conflicting conclusions regarding the overall benefits or costs of object displays. Instead, the intention is to reexamine four fundamental justifications that have been offered as rationale for assigning value to an object display. Within this context, the design and evaluation of an object display are described to support the perception of aircraft stall conditions.

The first of these four justifications is based more on HFE design principles than on a fundamental theory of information processing. It is simply the assertion that a single object representation of several variables generally produces less clutter and uses scarce display space more economically than the separate representation of several one-dimensional indicators. Stated directly, visual work load is driven upward by the number of displayed objects (Yeh & Wickens, 1988). The remaining three justifications are derived more directly from fundamental theoretical research of human information processing. The first of these relates to the concept of the *object file* proposed by Kahneman (Kahneman & Henik, 1981; Kahneman & Treisman, 1984).

The Object File

Based on his research and that of others (e.g., Lappin, 1967), Kahneman proposes that the allocation of attention to an object facilitates the processing of all of its constituent properties. That is, all attributes of a single object are processed in parallel, as each perceptual attribute that activates its node in a mental "object file" will automatically and in parallel activate the other attributes stored in the same file. While there is no competition between attributes <u>within</u> an object file, the ability to divide attention <u>between</u> objects is more limited. Such a view has been supported by a number of studies (e.g., Duncan, 1984; Kahneman & Chajczyk, 1983; Kahneman & Treisman, 1984; Kramer, Wickens, & Donchin, 1985; Lappin, 1967).

At a perceptual level, the object file theory implies that there is little competition for attention between the dimensions of an object. Hence, object displays should benefit performance for all tasks, regardless whether integration, divided attention, or focused attention is involved (Carswell & Wickens, 1988). Costs to performance will only be observed when the processing of these dimensions elicits conflicting responses, that is, when two "contradictory" nodes of an object are activated, resulting in conflict at the response stage (e.g., Kahneman & Henick, 1981).

Proximity Compatibility Principle

The second theoretical justification is based on the *proximity compatibility* principle (Andre & Wickens, 1989; Barnett & Wickens, 1988;

Carswell & Wickens, 1987), a theory-based principle of display design derived from early studies of comparative graphics (see Carswell & Wickens [1988] for a review and Garner's [1970; 1974] original observation of task interactions with integral and separable display dimensions). The general assumption of this principle is that display compatibility depends on the relationship between the physical structure of the displayed information and the cognitive structure of the task demands.

The role of the object display in information integration and focused attention tasks has received a substantial amount of empirical investigation both in the laboratory (Barnett & Wickens, 1988; Carswell & Wickens, 1987; 1989; Casey & Wickens, 1986; Fracker & Wickens, 1989; Goettl et al., 1986; Jones & Wickens, in press) and in others (Beringer, 1987; Beringer & Chrisman, 1987; Boulette et al., 1987; Sanderson et al., 1989; Coury & Purcell, 1988; Goldsmith & Schvaneveldt, 1984; Jacob et al., 1976). Collectively, the results of these studies have confirmed the crossover interaction between task type (integration versus focused attention) and display proximity (object versus separate) dictated by the proximity compatibility principle. That is, the integration of display attributes into an object is beneficial to tasks that require the integration of these attributes, while this same display format produces a cost when attention must be focused on an isolated attribute of the display.

Emergent Features

The third theoretical justification was originally put forth by Pomerantz (Pomerantz, 1981; Pomerantz, Sager, & Stoever, 1977) whose empirical work has served to identify specific circumstances in which object display benefits should be most predominant. While display proximity may be produced by similarity of any number of possible features (e.g., proximity in space and common color [Andre & Wickens, 1989]), the proximity that is defined when the stimulus sources are represented as different dimensions of a single object has a special status in that combining dimensions into a perceptual object may often <u>configure</u> to produce *emergent features* (Pomerantz et al., 1977; Pomerantz, 1981, 1983).

Emergent features are particular properties of the object (such as the area or shape of a rectangle display, the angle formed between two legs of a triangle display, or the direction indicated by the apex of an isosceles triangle) that directly support the information integration requirements of the task, because the value of these features map onto critical levels of the results of the integration. For example, the shape and size of a rectangle display (an object whose height and width vary) are emergent features. If an integration task requires assessing the product of height and width, the required integration is directly served by the rectangular area. If the task requires monitoring the state when the two variables are equal, this integration is served by a square shape. Thus, the basic concept behind such a display feature is the belief that system operators intuitively respond faster and more appropriately to a directly interpretable visual indicator than they do to a collection of information sources that must be mentally integrated and interpreted (Scott, 1989).

Early empirical evidence in support of this belief was provided by Woods et al., (1981), who constructed an object display to serve the assessment of nuclear power plant safety parameters. Each parameter was scaled so that the connection of parameter indices produced an emergent feature--the shape of a polygon. When the system was operating in a normal fashion (i.e., safely), a regular polygon was formed. However, variations in system parameters that produced abnormal conditions resulted in a shift away from the regular symmetrical shape of the polygon. This emergent feature allowed subjects to more easily assess the status of system safety, a decision-masking process important for effective nuclear power plant operation.

Modifications and Implications

Emergent features are not restricted to object displays (Coury & Purcell, 1988). In fact, research by Sanderson, Flach, Buttigieg, and Casey (1989) demonstrated that carefully chosen emergent features in separate bar graph displays (the imaginary line connecting the tops of three vertically aligned bar graphs) can provide integration performance that is superior to an object display without those features. A similar concept has been employed in the design of the vertically aligned four engine indicators on the C141 aircraft display. The assessment of equal engine performance (an integration task) is revealed by a horizontal line across all indicators.

Object displays can produce emergent features to the extent that the original dimensions are represented as lines varying in length (i.e., spatial dimensions). In this case, the configuration of these dimensions in a contoured representation produces geometric objects that may change in size and shape, the two emergent features of greatest relevance. But objects that are created by combining color and shape, or color and size (i.e., a colored bar graph) do not create emergent features. The combination of color with extent or angle dimensions, for example, does not create a new form that is uncharacterized by the two dimensions in isolation. In Pomerantz' (1981) terms, spatial and nonspatial dimensional pairs do not "configure" (Carswell & Wickens, 1990), and will not produce emergent features.

Research has revealed that combining spatial and nonspatial dimensions (color and shape) into a single object potentially facilitates initial parallel processing of both dimensions in a way that will support both focused attention <u>and</u> information integration tasks (Kahneman & Treisman, 1984; Treisman, 1986). The distinction between objects formed by configural and nonconfigural dimensions with regard to the proximity compatibility principle was revealed by Carswell (1988). She found that objects formed by spatial, configural dimensions produced the interaction predicted by the proximity compatibility principle, whereas nonconfigural objects, created by combining spatial and color dimensions, produced an overall benefit to performance on both focused attention and integration tasks.

THE PRESENT STUDY

In the present study, the authors have tried to assess the validity and design relevance of the proximity compatibility principle to a task that is quite prototypical of many information integration tasks in the world of complex systems. The specific task requirement is to monitor the set of variables necessary to appreciate the likelihood of an aircraft stall. The reason for choosing this task was not because the fixed wing aviation community needs an aircraft stall display. (Good airborne technology has already provided effective devices for computing the combination of variables that define critical stall conditions and presenting them by discrete annunciators such as horns or stick shakers.) Rather, the task was chosen because it is a prototype of many such integrated monitoring and warning tasks in complex analog systems, in which a number of variables configure or combine to create a derived variable of critical importance. At the same time, each of the variables in isolation is of operational importance to the human operator, and its value should therefore be made available for focused attention check reading or for mental integration with other variables that are not specific to the integration task at hand.

Specifically, the role of object representations and color together was examined by contrasting three display configurations (two objects and a bar graph). This comparison was made in two steps. First, it was investigated whether object integrality and the emergent features of the object display could, if carefully chosen, facilitate the perceptual integration task of estimating stall likelihood; however, as predicted by the proximity compatibility principle, this facilitation should also occur at the cost of focused attention. Thus, one feature of this study involved a comparison of focused attention and integration judgments with both object and bar graph representations of the stall information. The three relevant dimensions were combined to make an object (rectangle) that produced an emergent feature that directly correlated with the stall safety margin.

Assuming that the proximity compatibility principle holds, what does the designer do when both integration and focused attention are needed? Proximity compatibility, as it is stated, does not answer this question, since it articulates a tradeoff between those two kinds of judgments. However, the research of Carswell (1988) and the theory of object perception put forth by Kahneman and Treisman (1984) suggest that the use of color and shape together in a single object may facilitate parallel processing at a perceptual level that will help both focused attention and integration tasks. In particular, it is hypothesized that the color features of a single object might be processed without disrupting perception of the emergent feature represented by the shape.

Thus, a second objective of this study was to evaluate a third display that merged the manipulation of object representations with that of color to capitalize on both dimensions. As with the first object display, the same emergent feature was employed. However, the second object display borrowed from the color techniques used to enhance focused attention in the related study by Andre and Wickens (1989), so that each dimension of the object was now coded with a unique color.

Method

Design

In the bar graph display (see Figure 1), the three relevant indicators were represented as three adjacent bar graphs extending upward from a common base line and expressing, from left to right, airspeed, bank, and flap setting. The object display (see Figure 2) consisted of a rectangle positioned within the frame of the display to represent the three stall parameters. The value of the airspeed was represented by the position of the left corner of the rectangle along the lower horizontal axis of the display. The bank setting was represented by the height of the rectangle as scaled along the left vertical axis. Finally, the flap setting was represented by the width of the rectangle as scaled along the lower horizontal axis. This variable was scaled at half values. A reduction in scaling of flaps was

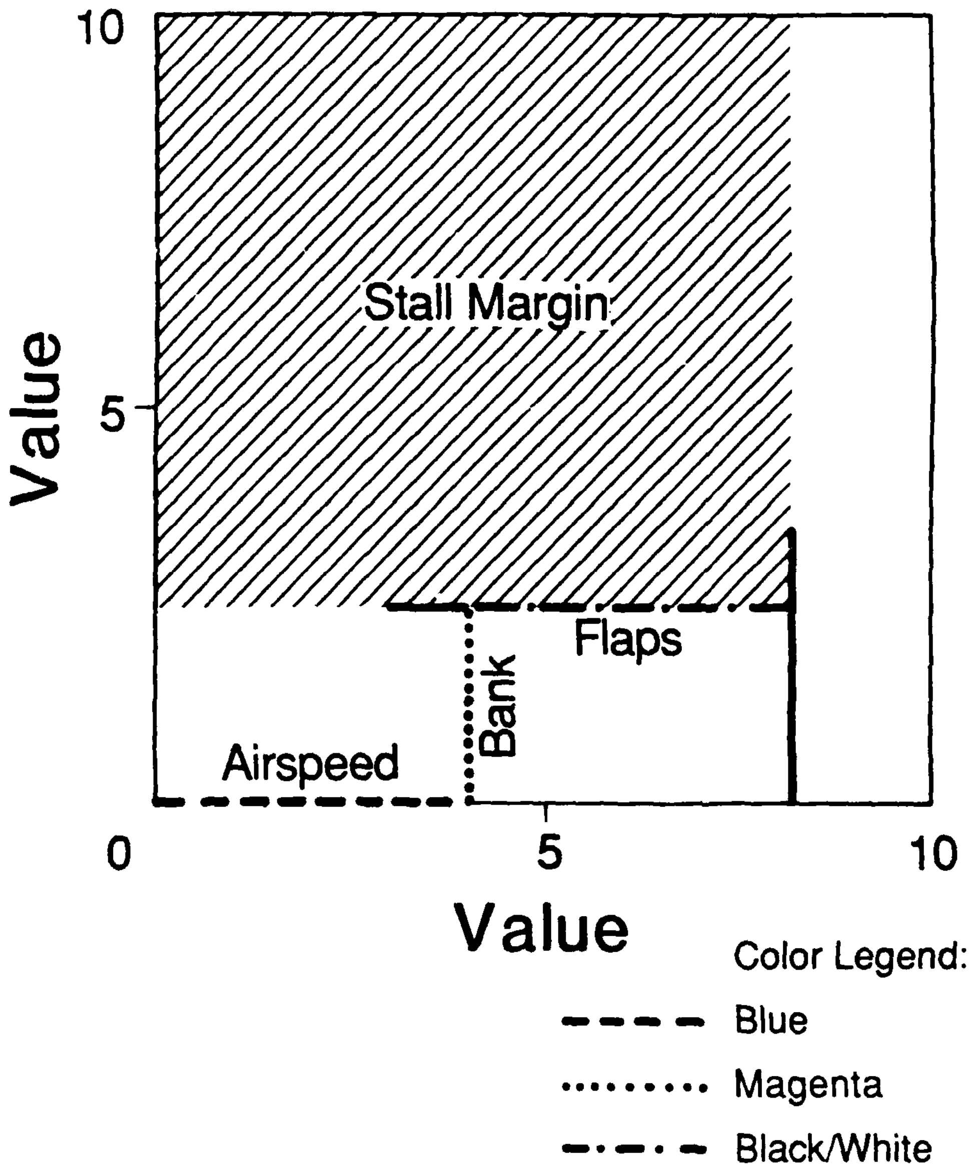

Figure 1. Object display used in the study. (The words on the display and the cross-hatched area are shown for illustrative purposes but were not actually present on the display.)

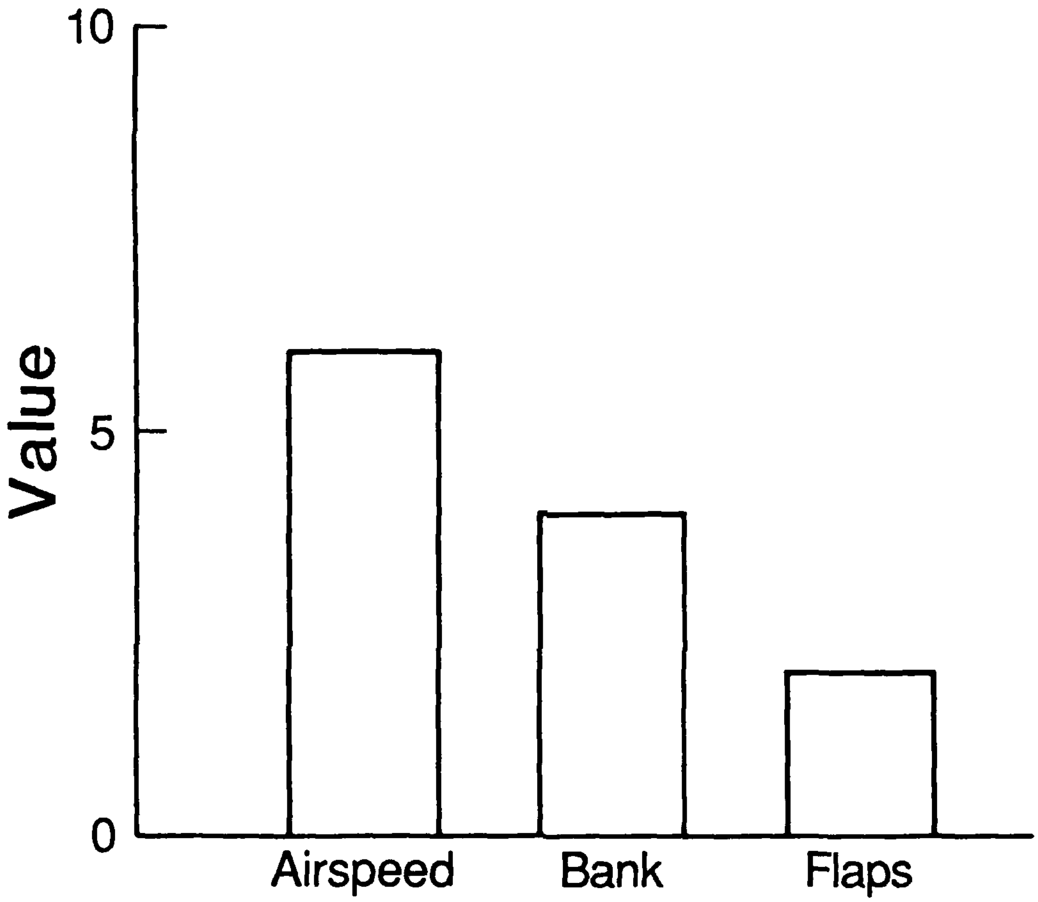

Figure 2. Bar graph display used in the study. (The words on the display are shown for illustrative purposes here but were not actually present on the display.)

advised because representing both flaps and airspeed at full scale would require a scale range of 20 arbitrary units on the horizontal axis, to accommodate maximum airspeed and maximum flap setting. The authors chose instead to limit the extent of the horizontal axis by reducing the scale value on the indicator (flaps) which was less important in the formula.

Four HFE features characterize this display. First, adhering to basic principles of display compatibility (Wickens, 1987), increasing the value of each of these parameters causes either a rightward (airspeed, flap setting) or upward (bank) movement of the right and top edges of the rectangle, respectively. Second, configuration as a rectangle conforms to Barnett and Wickens' (1988) conclusion that rectangles may facilitate integration without harming focused attention. Third, a single emergent feature directly represents the stall safety margin. This feature is the area of the rectangle, represented by the shaded area of Figure 2 in the upper left-hand corner of the display (the shading in the figure is for illustrative purposes only and was not present in the display). The "gain" in the changes of the three variables was separately adjusted so that the rectangular area was inversely related to the proximity to stall conditions. For example, note that minimum airspeed and flaps and maximum bank will reduce the stall margin to zero. Because scaling of the "flaps" variable was halved, subjects were asked to double the displayed flaps reading in giving their answer to that focused attention probe.

Finally, a fourth feature capitalizes on the psychophysics of the perception of a rectangular area. Human perception is such that changes in the area of small rectangles are perceived much more readily than equal changes in the area of larger rectangles. Hence, the emergent perceptual feature of the display is nonlinearly related to objective rectangle area. In fact, this feature is compatible with both the intended meaning of the display, in which changes in parameters near the stall region are far more critical than changes far away, and with the nonlinear properties of the stall formula itself.

In the color-coded version of the object display, illustrated by the legend shown in Figure 2, the extent of the bottom border corresponding to airspeed and the top border corresponding to flap setting were colored blue and black-white, respectively, while the vertical extent to the rectangle corresponding to bank was colored magenta. The remaining lines on the display were colored white (in the figure, these colors are represented by line texture).

Procedure

Displays were viewed on an IBM color monitor driven by an IBM-XT with an enhanced graphics adaptor (EGA) board. Subjects were seated directly in front of the screen at a distance of 50 cm and viewed the display for 1.5 seconds. Immediately after display termination, subjects were prompted with one of two task probes, using a retrospective probe technique. The subjects' primary task was to integrate the values of the three stall parameters to determine the stall safety margin on a scale from 1 to 10; safer flying conditions were denoted by higher values. The correct formula for the stall safety margin was approximately based on an analytic representation of the dynamics of a light aircraft, bearing a positive relation to airspeed and flaps and a negative relation to bank (see Appendix). Airspeed was the dominant factor in the equation, and interactive components were included so that nonoptimal settings of flaps and bank had greater impact at low airspeeds.

On the average, subjects were prompted with the integration task probe 75% of the time. The other 25% of the task probes required the subjects to recall the specific value of one of the indicators (focused attention) on a scale from 0 to 10. Task type was signaled to the subjects by one of the words stall, airspeed, bank, or flaps displayed on the screen immediately after termination of the information display. Responses to all probes were entered using the keyboard, and instructions were given to respond as quickly and as accurately as possible. Subjects were given feedback showing their response and the correct response for each trial. Three seconds after their response, subjects were automatically cued for a new trial with the presentation of a centrally located fixation cross.

All subjects were given explicit instructions concerning the method for determining the stall safety margin, followed by a series of 10 practice trials to ensure a proper conceptual knowledge of the program formula. In addition, for those subjects in the two object display conditions, the nature of the emergent feature (the projected rectangle area) and its direct relation to the stall safety margin were explained.

Thirty subjects (undergraduates at the University of Illinois) were paid to participate in the experiment. All subjects had normal or corrected-to-normal vision. Subjects viewing the multicolored object display were screened for their ability to perceive the colors used (by self report). Subjects participated in a 1-hour session during which they were exposed to one of the three display formats: the monochrome object, the multicolor object, or the bar graph display. They completed a total of 180 trials comprised of 6 blocks of 30 trials each. Subjects had no prior flight experience.

Data Analysis

Mean performance across the six blocks of trials for each of the dependent variables was submitted to an analysis of variance (ANOVA). This ANOVA revealed a significant improvement in performance over the six blocks for all three display formats, $p < .05$. Because of these learning effects, the accuracy and latency of response for the three display configurations, which were averaged over the last two blocks (60 trials), were submitted to the final analysis. Focused attention performance was assessed by averaging the data for both airspeed and bank setting recall. Recall of the flap setting was not considered in the analysis because this variable was represented at half values in the object displays (and thus had to be multiplied by 2 to derive the correct value) and was represented directly at whole values in the bar graph display. Thus, the task of recalling the flap setting was qualitatively different for the two types of displays. Error and latency data were compared across the three display formats and two types of tasks in a 3 by 2 mixed model ANOVA, with display varied between subjects and probe type varied within.

Results

Figure 3 plots the error data for the two types of tasks (integration and focused attention) as a function of the three display formats. A significant display by task interaction is evident in the data, $F[2,54] = 27.67$, $p < .001$. To examine this interaction more closely, two pairwise

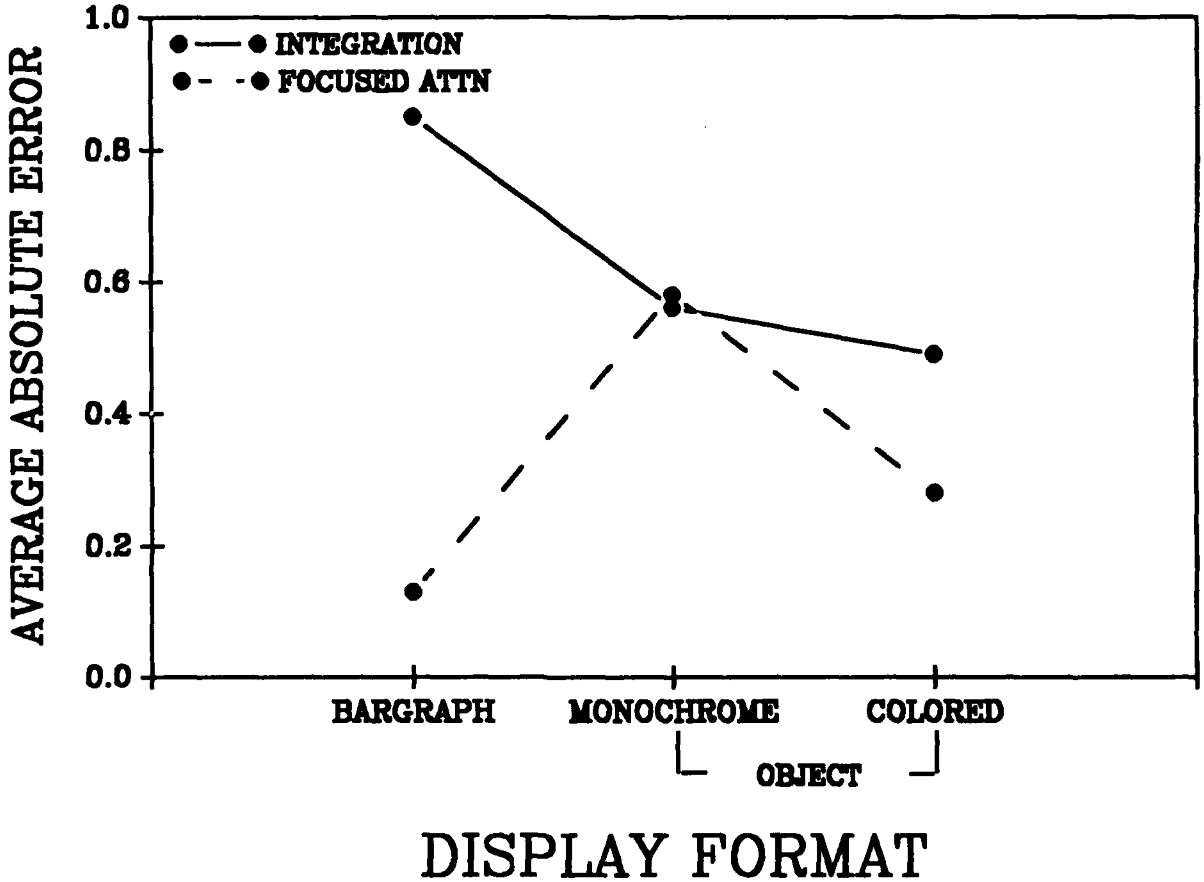

Figure 3. The effect of display format and task type on error. (The focused attention task probes are averaged over responses for airspeed and bank.)

analyses were performed on the six data points, the first contrasting the two monochrome displays (bar graph versus object, the four points on the left) and the second contrasting the two object displays (monochrome versus color, the four points on the right). Thus, the monochrome object served as a condition in both analyses.

The first of these analyses, shown by the solid line, revealed that the accuracy of integration performance was facilitated (i.e., error was reduced) by the monochrome object display relative to the bar graph display ($F[1,18] = 14.62$, $p < .01$), while the same display comparison revealed that the accuracy of reporting the occasional focused attention probes, shown by the dashed line, was facilitated by the bar graph display, $F[1,18] = 28.94$, $p < .001$. This finding represents a strong interaction predicted by the proximity compatibility principle.

The second analysis comparing the two object displays (monochrome and color) showed that the addition of separate colors to code the stall variables was successful in improving focused attention accuracy over the monochrome object display, $F[1,18] = 22.03$, $p < .001$. These results are compatible with the findings of Andre and Wickens (1989) which indicated that a separate color code can be used to improve focused attention performance. In contrast to that study, however, this improvement in focused attention accuracy was _not_ accomplished at the expense of poorer integration performance, because this performance did not change, and in fact slightly improved (non-reliably) with the colored object relative to the monochrome object ($F[1,18] = 1.96$, $p > .10$).

Figure 4 plots the reaction time data for the two task types as a function of the three display formats. As with the error data, a significant display by task interaction was observed in the reaction time data, $F[2,54] = 5.26$, $p < .01$. Following the same procedures used on the error data, this interaction was first examined by comparing the two monochrome displays (bar graph versus object). This analysis revealed no significant differences in reaction time to the focused attention probes between the monochrome object and the bar graph display ($F < 1$). However, object display benefits were observed for integration task performance relative to the bar graph display ($F[1,18] = 14.62$, $p < .01$), thereby producing an interaction of the weaker form, yet consistent with the proximity compatibility principle.

A comparison of the two object displays (monochrome and color) for focused attention reaction time revealed a marginally significant difference indicating that focused attention reaction times with the colored object were slower than with the monochrome object, $F[1,18] = 4.05$, $p < .10$. Similarly, reaction times to the integration task were slower with the colored object than with the monochrome object, $F[1,18] = 4.30$, $p < .05$. This trend is in contrast to the error data in which slightly better integration performance and significantly better focused attention performance were observed for the colored object display relative to the monochrome object display.

Thus, a speed-accuracy tradeoff appears to be induced by the use of color in the object so that accuracy of performance is improved at the expense of delayed latencies in response. For the focused attention task, however, this tradeoff appears to be one that favors the colored object display. That is, the significant gain in accuracy of performance relative to the monochrome object ($F[1,18] = 22.03$, $p < .001$) can be viewed as more pronounced than the marginally reliable loss in speed of response, $F[1,18] = 4.05$, $p < .10$. For the integration task, the tradeoff appears to favor the monochrome object.

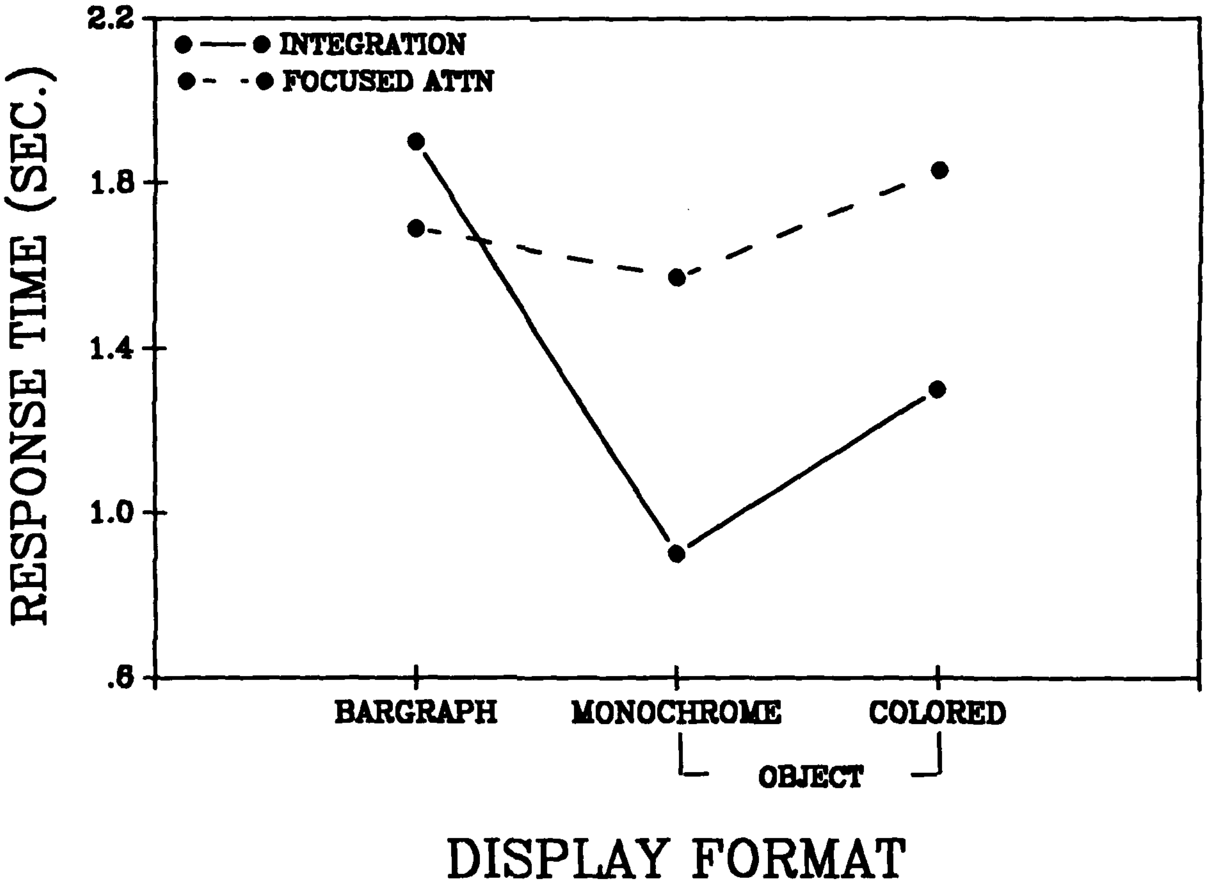

Figure 4. The effect of display format and task type on response time. (The focused attention task probes are averaged over responses for airspeed and bank.)

That is, the nonsignificant gain in accuracy shown by the colored object relative to the monochrome object ($F[1,18] = 1.96$, $p > .10$), does not compensate for the significant loss in processing speed, $F[1,18] = 4.30$, $p < .05$.

Clearly, these data represent the "no free lunch" principle that is inherent in the proximity compatibility principle. Considered collectively across tasks and variables, no overall performance differences between the colored and monochrome objects exist. These data suggest that colored objects do not lead to an overall enhancement of parallel processing. Instead, a speed-accuracy tradeoff exists, and ultimately, design decisions should be based on the designer's criterion of whether speed or accuracy is more important. The addition of color produced slower but more accurate performance across both focused attention and integration tasks, although the latter accuracy gain was not significant. Within each of the two tasks, however, the color effect behaves as predicted by the proximity compatibility principle; the separate color scheme helps focused attention performance (in accuracy) more than it hurts it (in speed), while integration performance is hurt (in speed) more than it is helped (in accuracy) by the same separate color scheme.

GENERAL DISCUSSION

Collectively, the results of the present study have both theoretical and practical implications. Those characteristics are first described that speak to the theoretical implications and their relation to the proximity compatibility principle before the more practical aspects are addressed.

In the present study, the degree of object representation was manipulated to vary the degree of display proximity. With the two monochrome displays (object and bar graph), the results clearly replicated the strong interaction predicted by the proximity compatibility principle (Andre & Wickens, 1989; Barnett & Wickens, 1988; Carswell & Wickens, 1987). The spatially defined object display with an emergent feature degraded focused attention as it facilitated integration, relative to the bar graph display.

In a previous study (Andre & Wickens, 1989), color and spatial proximity were manipulated jointly, and the data from that study suggested that color coding was able to compensate for the weaknesses of displays that suffered from high spatial proximity with clutter. Here, color and object representation were combined with a similar strategy in mind. Could unique color borders compensate for the loss of distinctiveness of individual dimensions that resulted from their configuration as an object and caused focused attention performance to suffer? The answer to this question was a qualified "yes." When performance was measured in terms of accuracy, the distinctively colored borders improved performance significantly on the check reading task and left integration performance unaffected (actually a small but nonsignificant improvement).

It is apparent from Figure 4 that the color information took some extra time to process, resulting in the cost to response time of 400 msec for integration and 200 msec for focused attention. This cost is of a sufficient magnitude to emphasize the point that color processing is not necessarily automatic or preattentive. When color is relevant to the task, the useful information it provides takes time to process. The current data suggest that the extra time (200 to 400 msec) is probably worth the benefit provided by increasing the accuracy of check reading, since the accuracy of integration was not disrupted by color. However, these data stand in partial contrast to findings that color and shape may be processed in parallel (Carswell, 1988; Kahneman & Treisman, 1984). This difference may reflect the more complex level of cognitive processing required of the displayed information in the current study.

Applications to Display Design

The object display is an emerging technology whose utility has been debated (Sanderson et al., 1989) but has found potential applications in the aircraft cockpit (Lovesey, 1986; Taylor, 1987), and the nuclear power control room (Woods et al., 1981), as a useful technique for reducing display clutter. Various researchers have studied the effects of these displays on performance in a variety of tasks, often reaching conflicting conclusions about their effectiveness. The current data reinforce the view that a key feature to establishing the success of object displays lies in their appropriate configuration to create emergent features that convey critical task-related information to the operator.

CONCLUSION

Recent efforts in visual display design research have greatly contributed toward the design of compatible display interfaces for complex systems. The successful application of the principles outlined in this study highlights the importance of providing compatibility between the cognitive structure of the task process and the perceptual structure of the displayed information. However, future research must try to quantify some of the critical display and task characteristics that have been cited in this report. This information will undoubtedly allow system designers to make comparisons more easily across display formats and task requirements. In fact, such efforts have already been undertaken (Palmiter & Elkerton, 1987; Tullis, 1983) and are in the future interest of the authors.

In summary, the object display has emerged as a flexible display format that easily configures to create emergent features and provides an efficient, economical means for presenting multiple sources of information that must be integrated and independently processed. Moreover, the object display serves as one example of a technological display "tool" whose inherent flexibility can be usefully exploited by valid HFE design principles. The authors are optimistic that the importance of this notion was exemplified in the present study.

REFERENCES

Adams, J. A. (1989). Human factors engineering. New York: Macmillan.

Andre, A. D., & Wickens, C. D. (1989). Proximity compatibility and information display: The effects of space and color on the analysis of aircraft stall conditions (Technical Report ARL-89-3/AHEL-89-2). Savoy, IL: Aviation Research Laboratory, University of Illinois.

Barnett, B., & Wickens, C. D. (1988). Display proximity in multicue information integration: The benefits of boxes. Human Factors, 29(5), 170-195.

Beringer, D. B. (1987). Peripheral integrated status display. Displays, 1, 33-36.

Beringer, D. B., & Chrisman, S. E. (1987). A comparison of shape/object displays, quasi-shape displays, and conventional univariate indicators: Integration benefits of the "nearer to thee" effect? In Proceedings of the 31st Annual Meeting of the Human Factors Society. Santa Monica, CA: Human Factors.

Boulette, M. D., Coury, B. G., & Bezar, N. A. (1987). Classification of multidimensional data under time constraints: Evaluating digital and configural display representations. In Proceedings of the 31st Annual Meeting of the Human Factors Society, Vol.1 (pp. 116-120). Santa Monica, CA: Human Factors.

Carswell, C. M. (1988). Graphical information processing: The effect of proximity compatibility. Unpublished Ph.D. dissertation, University of Illinois, Urbana-Champaign, IL.

Carswell, C. M., & Wickens, C. D. (1986). Why not the object? In L. Marks (Ed.), Trends in Ergonomics/Human Factors (Vol. III).

Carswell, C. M., & Wickens, C. D. (1987). Information integration and the object display: An interaction of task demands and display superiority. Ergonomics, 30, 511-528.

Carswell, C. M., & Wickens, C. D. (1988). Comparative graphics: History and applications of perceptual integrality theory and the proximity compatibility hypothesis (Technical Memorandum 8-88). Aberdeen Proving Ground, MD: U.S. Army Human Engineering Laboratory.

Carswell, C. M., & Wickens, C. D. (1989). The perceptual interaction of graphical attributes in thirteen bivariate displays (Technical Report ARL-89-6/AHEL-89-3). Savoy, IL: Aviation Research Laboratory, University of Illinois.

Carswell, C. M., & Wickens, C. D. (1990). The perceptual integration of graphical attributes: configurality, graphical homogeneity, and object integration. Perception and Psychophysics, 47, 157-168.

Casey, E. J., & Wickens, C. D. (1986). Visual display representation of multidimensional system (Technical Report CPL-86-2). Champaign, IL: Cognitive Psychophysiology Laboratory, University of Illinois at Urbana-Champaign.

Cole, W. G. (1986). Medical cognitive graphics. Proceedings of the ACM, SIGCHI '86.

Coury, B. G., & Purcell, J. (1988). The bargraph as a configural and separable display. In Proceedings of the 32nd Annual Meeting of the Human Factors Society, Vol. 2 (pp. 1361-1365). Santa Monica, Ca: Human Factors.

Duncan, J. (1984). Selective attention and the organization of visual information. Journal of Experimental Psychology: General, 113, 501-517.

Fracker, L., & Wickens, C. D. (1989). Resources, confusion, and compatibility in dual axis tracking: Displays, controls, and dynamics. Journal of Experimental Psychology: Human Perception & Performance, 15, 80-96.

Garner, W. R. (1970). The stimulus in information processing. American Psychologist, 25, 350-358.

Garner, W. R. (1974). The processing of information and structure. Hillsdale, NJ: Erlbaum Associates.

Goettl, B. P., Kramer, A. F., & Wickens, C. D. (1986). Display format and the perception of numerical data. In Proceedings of the Human Factors Society 30th Annual Meeting, Vol. 1 (pp. 450-454). Santa Monica, Ca: Human Factors.

Goldsmith, T., & Schvaneveldt, R. (1984). Facilitating multi-cue judgments with integral information displays. In J. Thomas and M. Schneider (Eds.), Human factors in computing systems (pp. 243-270). Norwood, NJ: Ablex.

Jacob, R. J. K., Egeth, H. E., & Bevan, W. (1976). The face as a data display. Human Factors, 18, 189-200.

Jones, P. M., & Wickens, C. D. (in press). The display of multivariate information: The effects of auto- and cross-correlation, reliability, and heterogeneity. Human Performance.

Kahneman, D., & Chajczyk, D. (1983). Tests of the automaticity of reading: Dilution of stroop effects by color-irrelevant stimuli. Journal of Experimental Psychology: Human Perception and Performance, 9, 497-501.

Kahneman, D., & Henik, A. (1981). Perceptual organization and attention. In M. Kubovy and J.R. Pomerantz (Eds.), Perceptual Organization (pp. 181-209). Hillsdale, NJ: Lawrence Erlbaum Associates.

Kahneman, D., & Treisman, A. M. (1984). Changing views of attention and automaticity. In R. Parasuraman, R. Davies, & J. Beatty (Eds.), Varieties of Attention. New York: Academic Press.

Kramer, A. F., Wickens, C. D., & Donchin, E. (1985). Processing of stimulus properties: Evidence for dual-task integrality. Journal of Experimental Psychology: Human Perception and Performance, 11, 393-408.

Lappin, J. S. (1967). Attention in the identification of stimuli in complex displays. Journal of Experimental Psychology, 75, 321-328.

Lovesey, E. J. (1986). The use of an air combat simulator in cockpit display development. In Proceedings of a Symposium entitled "Developments in Information Presentation to Aircrew" (Vol. 2, pp. 13.1-13.9). North Luffenham, England: Air Standardization Coordinating Committee.

MacGregor, D., & Slovic, P. (1986). Graphic representation of judgmental information. Human-Computer Interaction, 2(3), 179-200.

Mahaffey, D. L., Horst, R. L., & Munson, R. C. (1986). Behavioral comparison of the efficacy of bar graphs and polar graphics for displays of system status. In IEEE Proceedings of the International Conference on Systems, Man, and Cybernetics, 1514-1519.

Palmiter, S., & Elkerton, J. (1987). Evaluation metrics and a tool for control panel design. In Proceedings of the 31st Annual Meeting of the Human Factors Society. Santa Monica, CA: Human Factors.

Pomerantz, J. R. (1981). Perceptual organization in information processing. In M. Kubovy and J. R. Pomerantz (Eds.), Perceptual Organization (pp. 141-180). Hillsdale, NJ: Lawrence Erlbaum Associates.

Pomerantz, J. R. (1983). Global and local precedence: Selective attention in form and motion perception. Journal of Experimental Psychology: General, 112, 516-540.

Pomerantz, J. R., Sager, L. C., & Stoever, R. J. (1977). Perception of wholes and their component parts: Some configural superiority effects. Journal of Experimental Psychology: Human Perception and Performance, 3, 422-435.

Sanderson, P. M. (1986). Skills, displays, and decision support. In E. Hollnagel, G. Mancini, and D. D. Woods (Eds.) Intelligent Decision Support in Process Environments. New York: Springer-Verlag.

Sanderson, P. M., Flach, J., Buttigieg, M. A., & Casey, E. J. (1989). Object displays do not always support better integrated task performance. Human Factors, 31(2), 1-16 and 183-198.

Scott, W. B. (1989). Simulator, flight tests validate integrated pictorial cockpit display. Aviation Week & Space Technology, 130(2), 51-53.

Taylor, F. M. (1987). Workload management in military cockpits. Present insights. In Proceedings on Symposium in Military Aircraft. Royal Aeronautical Society, London.

Treisman, A. M. (1986). Properties, parts, and objects. In K. Boff, L. Kaufman, and J. Thomas (Eds.), Handbook of perception and human performance (Vol. II), cognitive processes and performance (pp. 35-70). New York: Wiley.

Tullis, T. S. (1983). The formatting of alphanumeric displays: A review and analysis. Human Factors, 25(6), 657-682.

Vicente, K., & Rasmussen, J. (1988). On applying the skills, rules, knowledge framework to interface design. In Proceedings of the 32nd Annual Meeting of the Human Factors Society, Vol. 1 (pp. 254-258). Santa Monica, Ca: Human Factors Society.

Wickens, C. D. (1987). Ergonomic-driven displays: A set of principles of the perceptual-cognitive interface. In Proceedings of the 4th Mid-Central Ergonomics/Human Factors Conference.

Woods, D. D., & Roth, E. M. (1988). Cognitive engineering: Human problem solving with tools. Human Factors, 30(4), 415-430.

Woods, D. D., Wise, J., & Hanes, L. (1981). An evaluation of nuclear power plant safety parameter display systems. In Proceedings of the 31st Annual Meeting of the Human Factors Society, Vol.1 (pp. 110-114). Santa Monica, CA: Human Factors.

Yeh, Y-Y., & Wickens, C. D. (1988). Dissociation of performance and subjective measures of workload. Human Factors, 30(1), 111-120.

APPENDIX

STALL DANGER CALCULATION

STALL DANGER CALCULATION

Factors influencing stall speed (SS: speed at which aircraft will stall).
Flaps (-) More flaps produce lower stall speed (SS).
Bank (+) More bank produces greater stall speed.
Airspeed (AS) does not affect stall speed, but decreasing airspeed reduces the margin of safety (AS-SS), so that when airspeed = stall speed, stall results.
Stall margin (SM) = AS - SS

$$\text{Stall Danger} = \frac{1}{SM} = \frac{1}{(AS - SS)+.1}$$

Bank (B) and flaps (F) determine stall speed as follows:
Both are expressed in units 1-10 (min-max) reciprocally related to each other, such that increases in one can compensate for decreases in the other, but bank is more important than flaps.

Therefore:

$$SS = \frac{50(1+.2B)}{(1+.1F)}$$

Thus, when both B and F = 0, SS = 50 knots, and AS = 50 knots (aircraft is flying at stall speed)

$$\text{then, stall danger (criterion value)} = \frac{1}{0+.1} = 10$$

$$\text{Thus, the final formula reads: stall danger} = \frac{1}{\left(AS - 50\,\frac{(1+.2B)}{(1+.1F)}\right) + 0.1}$$