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Graphical Displays: Implications for Divided Attention, Focused Attention, and Problem Solving

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When completing tasks in complex, dynamic domains observers must consider the relationships among many variables (e.g., integrated tasks) as well as the values of individual variables (e.g., focused tasks). A critical issue in display design is whether or not a single display format can achieve the dual design goals of supporting performance at both types of tasks. We consider this issue from a variety of perspectives. One relevant perspective is the basic research on attention and object perception, which concentrates on the interaction between visual features and processing capabilities. The principles of configurality are discussed, with the conclusion that they support the possibility of achieving the dual design goals. These considerations are necessary but not sufficient for effective display design. Graphic displays map information from a domain into visual features; the tasks to be completed are defined in terms of the domain, not in terms of the visual features alone. The implications of this subtle but extremely important difference are discussed. The laboratory research investigating alternative display formats is reviewed. Much like the attention literature, the results do not rule out the possibility that the dual design goals can be achieved.

INTRODUCTION

Since the early 1980s there has been a considerable amount of interest in graphic displays. This interest has been motivated in part by the increased availability of display technology and in part by a recognition of the need and potential benefits of centralized decision support in complex systems. With older technologies most interfaces have been limited to a single-sensor, single-display design. That is, each display presents the value of a single measurement. Even though this type of interface may make the data required to complete domain tasks available, it often does not provide the *information* necessary to support an observer in decision making. Woods (1991) makes an important distinction between design for "data availability" and design for "information extraction." Designs that consider data availability alone often leave to the observer the burden of collecting relevant data, maintaining these data in memory, and mentally integrating these data to arrive at a decision. This requires extensive

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knowledge, taxes limited cognitive resources (attention, short-term memory), and therefore increases the probability of poor decision making and errors.

There appears to be a clear consensus that performance can be improved by providing displays that allow the observer to utilize the more efficient processes of perception and pattern recognition instead of requiring the observer to utilize the cognitively intensive processes of memory, integration, and inference (Rasmussen and Vicente, 1989; Vicente and Rasmussen, 1990; Wickens and Andre, 1990; Woods, 1991). One way to accomplish this is by collecting and integrating information in centralized displays that utilize geometric object formats. For example, Woods, Wise, and Hanes (1981) adapted the original design of Coekin (1970) in developing a display that presents information concerning the health of a nuclear power plant: More than 100 individual sensor values are mapped into an octagon. This display is currently in use in the safety parameter display systems of several nuclear power plants.

The advantage of this type of display lies in the exploitation of humans' exquisite pattern recognition capabilities. Mapping multiple process variables into a single geometric form provides high-level visual properties, such as closure and symmetry. These properties can provide important information about the domain. For example, in the octagon display of Woods et al. (1981), the vertices of the polygon are dynamically scaled so that a regular polygon represents normal conditions whereas distortions in the polygon's symmetry represent a developing abnormality. In addition, particular types of abnormalities are associated with characteristic or "signature" distortions of the geometric object. Thus this type of display has the potential to improve decision-making performance by shifting the burden of responsibility from cognitive processes that are severely limited (e.g., working memory) to cognitive processes that, with learning, are virtually unlimited (e.g., object perception and pattern recognition).

Although there is general consensus that this type of display has the potential to improve human-machine system performance, there is less agreement on the principles or heuristics that should be used as design guidelines. Is the simple act of assigning variables to parts of geometric objects sufficient to improve performance when more than one variable must be considered (an *integration* task)? Will performance at tasks that require the consideration of individual variables (a *focused* task) suffer as a result of their incorporation into a geometric object? How well does the visual representation support problem solving? The present paper will examine these and other issues that are critical to the effective design of this type of display.

ATTENTION AND OBJECT PERCEPTION: VISUAL FEATURES

A variety of terms have been used to describe displays such as the octagon display, including *integral, configural,* and *object* displays. Performance with this type of display is often contrasted to performance with *separable* displays. It is no coincidence that these terms have been borrowed from the basic research investigating attention and object perception. The goal of that research is to identify the factors that control the distribution of attention to visual stimuli. Critical issues include the following: What are the fundamental perceptual units in objects? Is the perception of the *parts* of an object secondary to the perception of the *whole* object, or vice versa? How do parts group into wholes? Is competition for attentional resources between objects, within objects, or some combination thereof? What are the inherent relationships that exist between stimulus dimensions?

Attention Tasks and Dimensional Relationships

Garner (1970, 1974; Garner and Felfoldy, 1970) was one of the first to discuss the dimensional structure of stimuli. This work has been continued and extended by Pomerantz (1986; Pomerantz and Pristach, 1989; Pomerantz, Sager and Stoever, 1977) and has been generalized to issues of display design by Carswell and Wickens (1987). One task that has been used to examine the dimensional structure of stimuli is speeded classification: Observers are presented with a pair of stimuli and then required to make a discrimination based on the nature of the stimuli that are presented. (Other tasks include similarity judgments, categorization, and conjunctive visual search. See Treisman [1986] for an extensive review of the basic literature on object perception.) Typically the stimuli are varied on two or more dimensions, and each dimension can assume one of two values, as illustrated in the top portion of Table 1. In this case the two dimensions are pairs of parentheses that are presented in two spatial locations (left or right) and can assume one of two values (facing left or right), defining four possible stimulus combinations. Observers are presented with one of the four combinations, and the nature of the discrimination task is systematically changed across

TABLE 1

Stimuli, Discrimination Tasks, and Proposed Relationships between Stimulus Dimensions

Task	*Condition*	*Stimuli*	*Response*	*Critical Visual Feature*
Control (baseline)	1	((	a	Direction of right parenthesis
		vs. ()	b	
	2	)(	a	
		vs.))	b	
	3	((	a	Direction of left parenthesis
		vs.)(	b	
	4	()	a	
		vs.))	b	
Redundant (correlated)	5	((	a	Direction of right, left, or both parentheses
		vs.))	b	
	6	)(	a	
		vs. ()	b	
Selective attention (filtering)	7	((or)(	a	Direction of right parenthesis
		vs. () or))	b	
	8	((or ()	a	Direction of left parenthesis
		vs.)(or))	b	
Divided attention (condensation)	9	)(or ()	a	Direction of both parentheses
		vs. ((or))	b	
Separable	R = C = S > D			Divided attention cost No selective attention cost No redundancy gain
Integral	R > C > S > D			Divided attention cost Selective attention cost Redundancy gain
Configural	C = R >= D >= S			Smaller divided attention cost Selective attention cost No redundancy gain

Sources: Pomerantz (1986), Pomerantz and Garner (1973), Pomerantz and Pristach (1989), Pomerantz et al. (1977).

conditions by requiring the observer to attend to different aspects of the stimuli.

Four types of discrimination tasks have been defined, which are listed and illustrated in Table 1. In the *baseline* or *control task* (Conditions 1 through 4) only one of the two dimensions (e.g., the left or the right parenthesis) must be considered to make a discrimination, and the value of the irrelevant dimension is held constant. For example, in Condition 1, two of the four combinations of stimuli are presented individually, and an alternative response (a or b) is required for each. The correct response is determined by the relevant dimension (the direction of the right parenthesis) while the irrelevant dimension is held constant (the left-most parenthesis is always facing to the right).

The *selective attention*, or *filtering*, task is similar to the control condition in that the discrimination depends on the consideration of only one of the two dimensions. However, the second dimension is no longer held constant: It can assume all values across trials. In the *correlated*, or *redundant*, task, only stimuli that vary simultaneously in both dimensions are presented in a particular condition. Thus a discrimination can be made by attending to either of the two stimulus dimensions or by attending to both stimulus dimensions.

Finally, in the *divided attention*, or *condensation* task, variations in both stimulus dimensions must be considered to make the discrimination. Three qualitatively different relationships between stimulus dimensions have been proposed based on the pattern of performance across the preceding four classification tasks: separable, integral, and configural (Pomerantz, 1986). A sample pattern of results is illustrated in the bottom of Table 1.

Separable dimensions. A separable relationship is defined by a lack of interaction among stimulus dimensions. Each dimension retains its unique perceptual identity within the context of the other dimension, as indicated by equivalent performance on the control and the selective attention tasks. There is no filtering decrement: Observers can selectively attend to an individual dimension and ignore variations in the irrelevant dimension. Conversely, no new properties emerge as a result of the interaction among dimensions. Thus performance suffers in the divided attention tasks, where both dimensions must be considered to make a discrimination. This pattern of results suggests that separable dimensions are being processed independently. An example of separable dimensions are color and shape: The perception of color does not influence the perception of shape and vice versa.

Integral dimensions. An integral relationship is defined by a strong interaction among dimensions such that the unique perceptual identities of individual dimensions are lost. Integral stimulus dimensions are processed in a highly interdependent fashion: A change in one dimension necessarily produces changes in the second dimension. In fact, Garner and Felfoldy (1970, p. 237) state that "in order for one dimension to exist, a level on the other must be specified." As a result of this highly interdependent processing, a redundancy gain occurs. However, focusing attention on the individual stimulus dimensions becomes very difficult, and performance suffers when attention to one (selective attention) or both (divided attention) dimensions is required. An example of integral stimulus dimensions is perceived color: It is a function of both hue and brightness.

Configural dimensions. A configural relationship refers to an intermediate level of interaction between perceptual dimensions. Each dimension maintains its unique perceptual identity, but new emergent properties are also created as a consequence of the interaction between them. For configural stimulus dimensions, performance is best for the control and redundancy tasks, slightly worse for the divided attention task, and worst for the selective attention task. There are really two significant aspects in this pattern of results. First, relative to integral and separable stimulus dimensions there is a smaller divided attention cost, which suggests that performance can be enhanced when both dimensions must be considered to make a discrimination. Second, there is an *apparent* failure of selective attention (there are alternative interpretations of this cost; these will be discussed later).

Emergent features. The additional perceptual properties that arise from the interactions among configural stimulus dimensions have been referred to as *emergent features*. An example of emergent features in the stimuli of Table 1 include vertical symmetry [e.g., () and)(] and parallelism [e.g.,)) and ((]. Pomerantz and Pristach (1989, p. 636) stated that "emergent features may be global (i.e., not localized to any particular position within the figure), such as symmetry or closure, or they may be local, such as vertices that result from intersections of line segments." One example of how emergent features can influence performance has been referred to as the *configurality superiority effect* (Pomerantz, Sager, and Stoever, 1977). Pomerantz, et al. found that individual parentheses could be resolved more effectively when presented in a pair of closely spaced, normally oriented parentheses (such as those illustrated in Table 1) than when presented alone.

Summary. Subsequent research has revealed that stimulus dimensions rarely fall into these prototypical categories, at least as defined by the pattern of performance relationships among tasks presented at the bottom of Table 1. Cheng and Pachella (1984, p. 302) stated that "integrality may be a myth." Smith and Kilroy (1979, p. 285) found "dimensional combinations that are neither clearly integral nor separable." In a study particularly relevant for display design, Carswell and Wickens (1990) evaluated 13 combinations of perceptual dimensions (stimulus sets that were chosen to be representative of those found in graphic displays). They found no stimulus sets that satisfied all the operational definitions for integrality, two stimulus sets that satisfied the definitions for separability, and two that satisfied the definitions for configurality. For the design of graphic displays, separable and integral dimensions may represent idealistic end points and a continuum of configurality exists. Carswell and Wickens (1990, p. 165) reflect this belief, stating that "the perceptual-generative act of creating a graph may bias the choice of dimensions to those that are at least optionally separable (i.e., configural)."

Implications for Display Design

Several implications can be drawn from the principle of configurality. One is that the graphical elements of a display will interact to produce emergent features. This is critical for the design of graphic displays, especially for those intended to support performance at integration tasks (e.g., Sanderson, Flach, Buttigieg, and Casey, 1989). To the extent that these emergent features correspond to critical aspects of the domain, performance will be enhanced (this point will be discussed at length in subsequent sections).

Perceptual glue. A second implication is that a single display may support performance at both integration and focused attention tasks. This would appear to contradict the findings illustrating that configural dimensions produce a cost in performance for selective attention tasks. However, there are reasons to believe that this cost is apparent, not inherent. One potential explanation of the cost is that the perception of the whole takes precedence over perception of the parts and that information related to the parts is therefore less accessible. This notion has been explicitly referred to as *perceptual glue:* a hypothetical substance that binds individual graphic elements into a whole and makes the focusing of attention on the parts difficult or impossible. However, Pomerantz and Pristach (1989) stated:

> We need not hypothesize any perceptual glue to account for the subjective cohesiveness of forms or the *apparent failures of selective attention* to line segments. Subjects may prefer to attend to more salient emergent features than to less salient line segments, but this is not any sort of a failure. . . . One implication is that line segments do not lose their perceptibility when they are embedded within configurations of the type studied here. The process of grouping involves not losses of line segments but gains of emergent features. Observers may opt to attend to these novel features, but the line segments remain accessible; the forest does not hide the trees. (P. 642, emphasis added)

Salience. Before we proceed further, the notion of perceptual salience will be discussed. The term *salience* will be used synonymously with *visual prominence.* That is, it will be used to refer to how well a particular visual feature stands out relative to other features that are present. It should be noted that salience refers to the psychophysics of the stimulus. That is, the salience, or prominence, of a visual stimulus refers to how discriminable it is, independent of how useful this information is to an observer. It is also important to note that in dynamic task contexts, salience may depend on both the static geometric layout of the display elements and on the dynamic interaction of these display elements.

An alternative interpretation of the apparent cost for configural dimensions and selective attention tasks is related to perceptual salience. It is possible that objects are perceptual organizations the emergent or wholistic properties of which are more salient than are the elemental parts. Because emergent features are inherently more salient than are the elemental parts, observers are more likely to pay attention to the emergent features, which may result in apparent performance deficits. This does not mean that observers cannot, at their discretion, focus on the parts of an object when it is necessary to do so (an observation consistent with Garner's [1974] description of configurality as *optional separability*). Carswell and Wickens (1990) discussed this possibility and found large between-subject variability for filtering costs to support it. Thus whether a filtering cost is observed or not may depend on the salience of the visual elements relative to the emergent features, as well as on observer strategies and preferences.

Summary. The attention and object perception literature (in particular, the principle of configurality) leaves open the possibility that a single geometric display may be designed to support performance for both divided and focused attention tasks. One way to consider objects is as a set of hierarchical features (including elemental, configural, and global features) that vary in their relative salience. For example, Treisman (1986) observed that "if an object is complex, the perceptual description we form may be hierarchically structured, with global entities defined by subordinate elements and subordinate elements related to each other by the global description" (p. 35.54). Observers may focus attention at various levels in the hierarchy at their discretion, and in particular, there may be no inherent cost associated with focusing attention on elemental features.

DISPLAY SEMANTICS: THE MEANING BEHIND VISUAL FEATURES

The basic research on attention and object perception has important implications for the design of advanced graphic forms in applied domains. However, there are some fundamental limitations in extrapolating the conclusions of this research to display design. Graphic displays are more complex than the stimuli typically used in the basic literature. In addition, in dynamic task contexts, salience may depend on both the static geometric layout of the display elements and the dynamic interaction of these display elements.

More fundamentally, research on attention and object perception focuses on the relationship between the information-processing characteristics of the observer and the characteristics of the visual stimuli that are presented to the observer. The task is defined primarily in terms of the visual features that are present in the display. However, in human-machine systems a display is a representation of an underlying domain, and the user's tasks are defined by that domain rather than by the visual characteristics of the display itself.

Woods and Roth (1988) captured this fundamental difference in their conception of the "cognitive triad." They stressed that the quality of performance in human-machine systems is the result of three interactive and mutually constraining components: the cognitive demands produced by the domain of interest, the cognitive agent(s) that meet those demands, and the representation of the domain through which the agent experiences and interacts with the domain. In the basic attention research, the interaction between agents and representations is emphasized. There is no domain of interest standing behind the representation.

To complete tasks in complex, dynamic domains, observers must consider information regarding both high-level constraints (e.g., status of processes) and low-level data (e.g., output of sensors). The term *low-level data* refers to the measured values of individual process variables. In contrast, the term *high-level constraints* refers to relations that exist between these process variables. For example, a simple relationship might be the measured value of a variable compared with the goal for that variable. A more complex relation might require a number of variables to be considered (e.g., mass balance). In any complex system there will be a continuum of increasingly complex relations (properties or constraints) that, by definition, will characterize alternative system states. We use the terms *high-level constraints* and *low-level data* as end point labels that refer to this continuum.

Another way of characterizing the difference between these two approaches is in terms of syntax versus semantics. The physical appearance of graphic displays and how these characteristics interact with the perceptual capabilities of an observer are clearly an important consideration. We will use the term *syntax* when referring to this aspect of display design: the physical appearance of a display (What are the parts, what do they look like, and how do they fit together?). The research on attention and object perception focuses on syntax given that the tasks to be performed are defined primarily in terms of the visual characteristics of the display. However, for human-machine systems, what a display looks like must be considered in the context of what the display means; that is, what it represents in the context of problem solving. We will use the term *semantics* to refer to the meaning that lies behind the physical appearance of a display—What relationship does the visual form have to the underlying domain that it represents? This distinction has similarities to that made by Hutchins, Hollan, and Norman (1986) with respect to articulatory and semantic directness and, in a more general sense, to the observation made by Craik and Lockhart (1972) that words can be processed on the basis of their physical appearance, what they sound like, or what they mean.

One consequence of a process standing

behind the graphic is that the terms *integral, separable,* and *configural* are often used in ways that reflect the nature of the mapping from the process to the display rather than simply the properties of the graphic. The term *integral* is used for a display in which many process variables are mapped to a single display feature—for example, a safety alarm the status of which is a function of many system parameters. The term *separable* is used for a display in which each of the process variables is mapped to separate display features (as in single-sensor, single-indicator designs). The term *configural* is used for a display in which variables are mapped to elementary display features, but the features are organized in a way to produce configural or emergent features that map to process constraints. With this usage, the three terms are not specific to any visual form but refer to the mapping of the domain semantics onto the visual form. Thus the same graphical format (e.g., bar graphs) can be either separable, configural, or integral depending on the mapping to the process variables.

This dual meaning for the terms *integral, separable,* and *configural* has contributed to confusion in generalizing from basic research on visual attention to the applied problem of graphical interface design. We recommend alternative terms for the mapping of process semantics to graphical forms. *Categorical mapping* would be used for situations in which many process constraints (defined over multiple process variables) map to a single display feature. *Elemental mapping* (Woods, 1991) would be used when each of the process variables maps to separate display elements. This category represents the single-sensor, single-display format. Finally, *hierarchical mapping* would be used for situations in which variables are mapped to display elements and higher-order process constraints map to configural or emergent features of the display organization.

LITERATURE REVIEW

In this section we review and summarize the findings from laboratory research investigating the benefits and costs of alternative graphic forms. Historically this research has been posed in terms of a distinction between object displays and separate displays. In object displays several variables are mapped into a geometric object. However, more recently the term *object display* has been replaced by *configural display* (e.g., Sanderson et al., 1989). The term *configural* highlights the critical role of emergent features. In separate displays there are individual objects for each variable in the display. Performance with these two general types of display formats is typically contrasted on two general types of tasks: integrated and focused. In integration tasks a number of variables must be considered together (integrated) to reach a decision. In focused tasks an observer has to focus attention on, or selectively attend to, a single variable.

Experimental Methodologies

Four experimental methodologies have been identified. These methodologies differ in the types of tasks that observers are asked to perform and in the types of behavioral measurements that are obtained.

In the *signal detection methodology*, an observer monitors a dynamic system but does not control it. The graphic display is available continuously to the observer and changes dynamically as a function of changes in the domain. To perform integrated tasks, an observer must detect system abnormalities or detect deviations from the normal trends in the data; and there is ambiguity about when these events occur. To complete focused tasks, an observer must identify which of the individual variables exceeded a set point or deviated from the normal trend. Measurements of accuracy, latency, and behavioral metrics associated with the signal detection methodology (Hits, False Alarms, d' or A', and β) are obtained.

In the *multiple cue judgment methodology*, a static display is presented to an observer in a discrete fashion and usually remains available for visual inspection. The observer's task is to consider the data presented in the display and to arrive at a criterion estimate. The nature of the criterion estimate varies from study to study: It may be a categorical estimate of system state or a quantitative estimate of a criterion value. To arrive at this estimate, observers must consider all variables with respect to categorization rules or cue-criterion relationships. Direct measurements of performance at focused tasks are usually not obtained. Primary behavioral measurements are accuracy, latency, and those based on the Brunswick lens model (e.g., r_a, G).

In the *retrospective memory probe methodology* (RMP), an observer is asked to recall information about the underlying domain. Before a probe is administered, the display is removed from vision and the observer is forced to consult memory to perform the task. In addition, the observer is unaware of the exact probe to be completed or the exact time that the probe will occur: The observer may be in the process of completing another primary task or may not know which of several probes are to be performed until it is administered. These two aspects of the retrospective memory probe differentiate it from the other methodological categories. Measures of accuracy and latency are the primary behavioral measurements for the RMP methodology.

In the *system control methodology*, an observer monitors a continuously available dynamic display and controls a dynamic system. To complete this type of task an observer must extract information from the display(s), integrate the information, and compare it to performance goals. Control inputs must then be selected and executed, feedback from the display(s) must be obtained, and the cycle must be repeated if necessary. There are a number of behavioral measurements that can be obtained with the methodology: target-acquisition time, root-mean-square error, analyses of time histories (e.g., noting control reversals or submovements) and analyses in the frequency domain (e.g., describing functions).

Experimental Results

In this section the results of laboratory studies are organized and presented. Our criterion for inclusion in the sample is that performance with configural and separate displays was directly contrasted. One primary factor in organizing these results is the methodology that was employed in the study, as indicated by Figures 1 through 3 (a figure for the control methodology was not included). These figures were also designed to reflect the type of task (integrated or focused), the graphic format, the ordering of performance, and the statistical significance of each study that was reviewed (the key at the top of Figure 1 describes the symbology used to encode this information).

Two qualifications need to be made before we proceed with the literature review. First, in some cases the placement of a study required judgment by the authors. For example, the multiple cue judgment category contains some studies that do not use that methodology in the technical sense (these are the studies without Brunswick behavioral metrics). However, the benefit of providing broad categories to obtain an overview of performance outweighs the occasional study that does not fit squarely. The second qualification is that the summarized results also represent considerable judgment on the part of the authors. Although significant effects were usually reported in those studies, the supplemental analyses required to establish statistical significance between particular formats often were not. In these cases the size of the effect and the difference between the means associated with the formats were considered. Significant differences were reported only when there was fairly conclusive evidence (large effect size, large differences between means).

Signal detection methodology. The Carswell and Wickens (1987) study is representative of the methodology. Observers were required to monitor two dynamic systems, each of which had three process variables: two inputs and an output. In the integrated task (Experiment 1) the observers monitored continuously present dynamic displays for nonpredictable system failures. Normal system state was determined by a mathematical function (either additive or multiplicative) relating the two inputs to the output; a system failure occurred when the output deviated from the mathematical function. Thus a system failure could be detected only by considering the relationships among all three variables.

In Experiment 1 both separate displays (bar graph displays with a common baseline) and configural displays (two triangle displays in which the value of each variable determined the distance of each vertex from a common point on the baseline) were used. The results indicate that the configural display improved the latency of performance at the integrated task significantly. As illustrated in Figure 1, observers detected system failures in significantly less time with the triangle displays than with the bar graph displays. This is represented by the left-to-right ordering of the icons, the underscoring of these icons, and the highlighting of the triangular icon. (An icon is filled only when there is a clear statistical advantage for one of the two general display types.) For false alarms there was a significant three-way interaction effect indicating that under some experimental conditions, the separate displays produced better performance than the configural displays (and vice versa). This is indicated by the dashed line separating two sets of symbols in opposite order. However, the supplemental analyses reported in the paper were not sufficiently detailed to establish statistical significance between display formats. Thus the icons are not highlighted or underscored.

In the focused task (Experiment 2) observers monitored the six variables and reported when the value of an individual variable crossed a set point. As in Experiment 1, the displays were continuously available and changed dynamically; the set point crossings occurred at unpredictable times. Staggered bar graph displays and triangle displays were used. Dependent measures of accuracy, latency, and false alarms were obtained. No significant differences were found between displays for accuracy and false alarms. However, the staggered bar graph display produced significantly faster response times than did the triangle display.

In summary, Figure 1 reveals a fairly consistent pattern of results for experiments that used a signal detection methodology to assess performance in integrated tasks. This pattern of results indicates that configural display formats support performance more effectively than do separable display formats. Considering only the behavioral measures of accuracy and latency, all five studies found statistically significant evidence that configural displays facilitated performance.

In contrast, the results for focused tasks were much less clear cut. Only two studies found significant performance differences. Casey and Wickens (1986) found that a staggered bar graph resulted in superior accuracy over either of two configural formats (polygon and face). Carswell and Wickens (1987) found a staggered bar graph to result in smaller latencies than a triangle display. However, the majority of comparisons across studies showed no statistically significant dif-

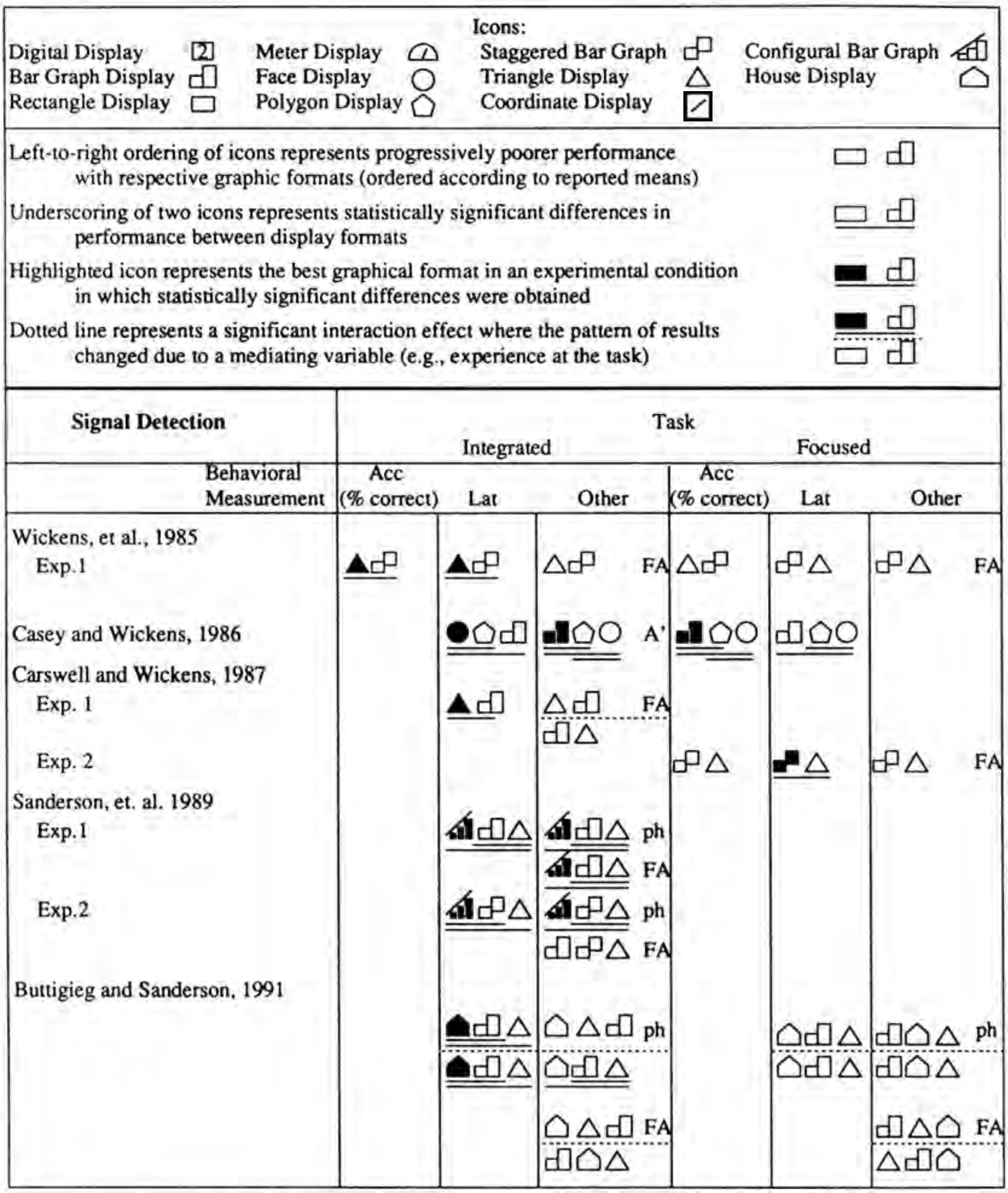

Figure 1. *Symbolic description of results from the signal detection methodology.*

ferences in performance. It is also important to note that in several instances (Buttigieg and Sanderson, 1991; Wickens et al., 1985), a single configural display supported performance in both integrated tasks (significantly) and focused tasks (nominally). This suggests that there is not necessarily a tradeoff between integrated and focused tasks for configural displays, as early theories had suggested (e.g., Carswell and Wickens, 1987).

Multiple cue judgment methodology. In a study that is representative of the methodology, Goldsmith and Schvaneveldt (1984) asked observers to consider several cues in order to produce a criterion value. Three cue-criterion relationships were used in the experiments: *additive, configural,* and *mixed.* In the additive cue-criterion relationship the two cues were added together to produce the criterion value. In the configural cue-criterion relationship the two cues were multiplied to produce the criterion value. In the mixed cue-criterion relationship the sum of the two cues was added to the product of the two cues to produce the criterion value. This multiple cue judgment task qualifies as an integrated task because the values of several cues must be considered with respect to the cue-criterion relationships in order to produce a criterion estimate.

The data were presented in a discrete fashion using static displays; the displays remained on the screen for visual inspection while an observer was forming the criterion estimate. The dependent variable was the correlation between the estimated and actual criterion value (r_a). Goldsmith and Schvaneveldt (1984) presented the cue values using several display formats, including a rectangle, two triangles, and a bar graph display. In all four experiments the configural display formats produced more accurate criterion estimations than did the bar graph display format.

To summarize, and as shown in Figure 2, the results of experiments that have used the multiple cue judgment methodology reveal a very consistent pattern of results, which indicates that performance with configural displays is superior to performance with separate displays for integrated tasks. The ordering of experimental means almost always favors configural displays relative to separable displays, and, in most instances, these differences were statistically significant (the only exception is the study by Coury, Boulette, and Smith, 1989). In short, the pattern of results for the multiple cue judgment methodology provides strong evidence that configural displays may be designed to improve the observer's performance in integrated tasks. Only one study (Goettl, Wickens, and Kramer, 1991) examined performance in a focused task. A significant advantage was found for the separable format.

Retrospective memory probe methodology. A representative study is that of Wickens and Andre (1990). Observers were presented with three variables in one of two display formats: a bar graph display or an imagined rectangular configural display. The displays were presented for a short duration (1.5 s) and then removed from the screen. On the majority of experimental trials an observer was required to perform an integrated task. However, on a small percentage of trials (25%) an observer was asked to remember the value of one of the three individual variables. The fact that the observer does not know which of the two probes will be administered and must rely on memory to complete the probe is characteristic of the methodology. For focused tasks Wickens and Andre (1990) found no significant differences between display formats in latency, whereas the accuracy of responses was facilitated significantly by a bar graph display. For integrated tasks significant advantages were found for the configural display in both accuracy and latency.

In summary, for integration tasks there is a consistent pattern of experimental results favoring configural displays relative to separate displays. In all studies that reported statistical analyses, significant advantages favoring configural displays were found. In both remaining studies (Wickens and Andre, 1988; Wickens et al., 1985) the differences in

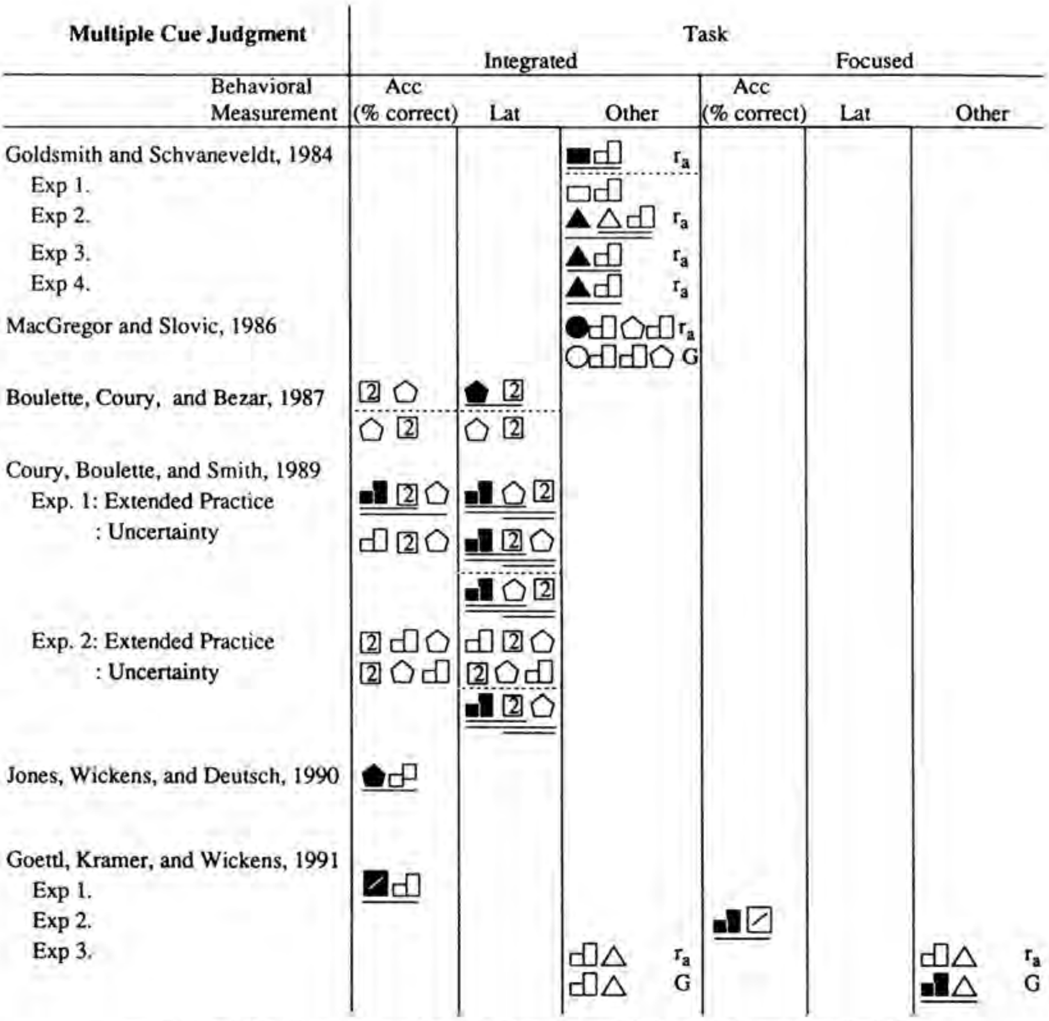

Figure 2. *Symbolic description of results from the multiple cue judgment methodology.*

means were large and the configural displays were favored. For focused tasks there is a relative lack of statistically significant results indicating a cost when data are presented in a configural format. Although three of the seven experiments revealed significant performance advantages for separate displays, in one study this finding was reversed. There is much less consistency in the ordering of means than found in the signal detection methodology. In fact, Figure 3 reveals an almost random ordering of means.

One concern about using the retrospective memory probe (RMP) methodology is that researchers using this technique have employed rather naive views of memory. It has been shown consistently that memory for details is unreliable (e.g., Bartlett, 1932; Bransford and Franks, 1972; Loftus, 1980). What is remembered is the gist or meaningful aspects

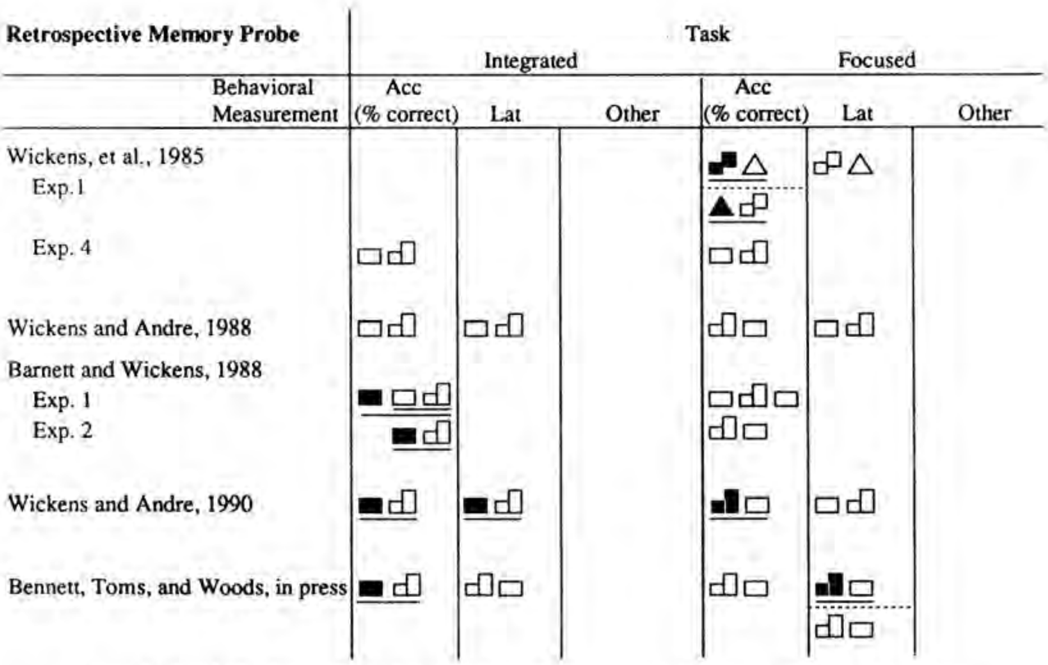

Figure 3. *Symbolic description of results from the retrospective memory probe methodology.*

of events. Thus the utility of the RMP methodology ultimately depends on the nature of the questions that are asked. Variables are more likely to be remembered if they are important in the context of the tasks that are being performed. A failure of recall may be an indication that a particular graphic format does not present this information in a fashion that facilitates extraction, storage, and recall by an observer. Conversely, a failure in recall could also indicate that the information has no relevance in the current problem-solving context. That is, a failure in recall could indicate that the experimenter has failed to ask semantically relevant questions, not a failure in display design.

For example, Vicente (1991) used a version of the memory probe methodology to evaluate display design. He compared memory for variables related to system state as a function of display format and experience level (expert-novice). An analysis of recall performance for all system variables indicated no significant differences related to display format or experience. However, when separate analyses were performed on meaningful and nonmeaningful system variables (as defined by the problem-solving context), significant performance differences became evident, but only for relevant variables.

System control methodology. Very little research has investigated performance on integrated and focused tasks in the context of manual process control. There are two reasons for this. First, in modern process control facilities most control functions are automated, with the human specifying set points and monitoring the process to detect abnormalities. Thus the human functions as a supervisor, and automatic control systems are tasked with direct control of the process. Second, control can be a complex skill that varies widely as a function of many factors (most important, observer experience) in addition to the factor of representation or display design. For this reason the control task is not a very sensitive experimental context within which to evaluate alternative display formats unless a subject pool of highly trained controllers is available. For example, Bennett, Toms, and Woods (in press) found large advantages in control performance for a configural display, relative to a bar graph display (an average of approximately 20 s in Experiment 2), that failed to reach statistical significance because of the large within-group variability.

However, generalizations might be drawn, with some caution, from work on multiaxis tracking. In a review of research on multiaxis integrated displays, Wickens (1986) concluded that "there is little doubt that *integrated displays* in which a single error indicator can make excursions in more than one orthogonal axis should be of considerable benefit to tracking performance" (pp. 39–50). Wickens (1986) points to two sources of benefit for integrated tasks. First, integration allows all axes to be within foveal vision. Thus deficits resulting from scanning and searching are minimized. One of the rationales behind safety parameter display systems (e.g., Woods et al., 1981) is to integrate the many variables that must be considered in evaluating a process within a single attentional field. A second source of benefit for integrated tasks that Wickens (1986) noted was that "for some kinds of tracking tasks the two axes of the controlled system are themselves 'naturally' integrated in the real world, so that display integration offers a more compatible representation with the operator's internal model of the system" (pp. 39–50).

As to costs associated with focused tasks, the classic study by Chernikoff and Lemay (1963) suggests that there is *no cost with integral displays*. Even when two axes had different dynamics (position-acceleration) and must be responded to using separate control sticks, performance with the integral format was equivalent to that for a separable display. In contrast, there was a cost associated with an integrated response stick. Thus interference was primarily attributable to response conflicts, not to an inability to perceive the separable dimensions within the integral display.

The control literature suggests, in summary, that configural formats may reduce costs of integration. As with the signal detection tasks, there does not seem to be a trade-off. Improvements in integrated task performance are not at the cost of focused performance.

Summary of Experimental Results

In the laboratory research on display design, observers are often required to collect and integrate information from the underlying domain, a form of integrated task. The empirical evidence strongly supports the advantage of more configural display formats. The benefits to performance are evident in all three methodologies that were reviewed in detail (see Figures 1, 2, and 3). By far the most common result is a statistically significant performance advantage favoring configural displays relative to more separate displays.

In addition to considering the relationships among variables, an observer must make decisions or take actions based on the values of the individual variables themselves (a focused task). Results from the signal detection and the retrospective memory probe methodologies reveal a mixed pattern of results that do not strongly support performance advantages for either general type of display format. The most common result is a lack of statistical significance between the general display types, as indicated by the relative lack of filled symbols in the columns for focused attention. When significant differences between display formats were found, they usually favored separate displays. However, in some cases there are performance advantages for the configural display of information, and in one study this performance advantage is statistically significant. Clearly, these results do not strongly support the existence of an inherent and unavoidable cost for the extraction of low-level data with configural formats.

PRINCIPLES OF DISPLAY DESIGN

In this section we will consider two principles of display design in light of the pattern of experimental results observed in the review: the principle of *proximity compatibility* and the principle of *semantic mapping.*

Proximity Compatibility

The first principle to be considered is display proximity, or the principle of proximity compatibility developed by Wickens and his colleagues (e.g., Carswell and Wickens, 1987). In its original version the theory emphasized the importance of the relationship between task demands and the graphical form of a display. The proximity of a display can be defined along two primary dimensions: physical metrics, such as spatial proximity or chromatic proximity, and geometric form (e.g., object versus separate displays). When individual variables are mapped into a closed geometric form, the display is high in display proximity; when each variable has its own unique representation (e.g., a bar graph), the display is low in proximity. The proximity of a task is similar to the definitions of integrated (high-proximity) and focused (low-proximity) tasks.

Briefly stated, the principle of proximity compatibility maintains that the display proximity should match the task proximity: Performance on integrated tasks (high proximity) is predicted to be facilitated by object displays; performance on focused tasks (low proximity) is predicted to be facilitated by separate displays. Thus this principle predicts a trade-off between integrated and focused attention.

Concept of objectness. There are several problems with this principle. The first is the concept of object display. A number of studies (e.g., Buttigieg and Sanderson, 1991; Sanderson et al. 1989) show that improved performance at integrated tasks is more closely tied to configural properties of visual forms (presence of emergent features) than to objectness per se. Object displays the emergent features of which do not correspond to process constraints do not support improved performance in integrated tasks; separable displays with configural properties that map to process constraints do show improved performance in integrated tasks. Thus the proximity of a display seems to depend more on configurality than on objectness. As is apparent from the review, there is a consistent pattern of improved performance for the integrated tasks when displays are defined in terms of configurality. It should be noted that subsequent versions of proximity compatibility have acknowledged the importance of emergent features (e.g., Wickens and Andre, 1990).

Performance trade-offs. A second problem is that the principle of display compatibility predicts a trade-off between integrated and focused benefits. That is, this principle suggests that configural displays will facilitate performance for integrated tasks but degrade performance for focused tasks. The literature review indicates a clear benefit for integrated task performance; however, there is little evidence of a cost. In several cases the same configural display results in significantly better performance for the integrated task and nominally better performance for focused tasks (e.g., Buttigieg and Sanderson, 1991). Although cases in which trade-offs occurred were found (e.g., Carswell and Wickens, 1987), these trade-offs may reflect a failure to consider salience of display elements when constructing configural displays.

Summarizing the results reveals only a weak form of interaction with improvement in performance for integrated tasks with configural displays but with few differences between display formats for focused tasks. In later papers Wickens recognized the weak form of interaction (e.g., Wickens and Andre, 1990, p. 63). However, implicit in the principle of display proximity is the notion of perceptual glue, which was discussed earlier in the section on attention and object perception: Perception of the parts is secondary to perception of the whole. For example, according to Wickens and Andre (1990, p. 65), the theory predicts, "It is harder to focus attention for check reading on a dimension when it is embedded within a single, contoured object than when it is represented as one of several separate indicators (e.g., bar graphs)." This prediction appears to be rather straightforward: Presenting data in configural displays will incur a cost relative to presenting information in more separable displays.

The results from the display literature do not provide strong support for this prediction. The most common finding is a lack of significant differences between configural and separate display formats. It should be noted, however, that when significant differences were found, they did tend to favor separable displays. As opposed to perceptual glue, the principle of configurality suggests that the parts never completely lose their identity relative to the whole. When the parts are configured to produce emergent features, information related to the parts is available alongside the high-level emergent features and can be focused on when so desired. However, that information is likely to be less distinctive than the emergent features.

Several implications for display design may be drawn. As Pomerantz (1986; Pomerantz and Pristach, 1989) stressed, the apparent cost for focused tasks may be a side effect attributable to imbalances in salience between emergent and elemental features. Thus the extraction of low-level data will depend on the perceptual salience of the graphical elements relative to the emergent features. The elemental features will be inherently less salient than the emergent features, and in some cases the difference will produce a cost in performance. This analysis suggests that if the perceptual salience of the elemental features is increased relative to the emergent features, this potential cost may be offset. This might be accomplished through a variety of methods, including color coding the graphical elements (Wickens and Andre, 1990), maintaining and emphasizing scale (e.g., Dolan, Elvers, and Schmidt, 1991), spatially separating the graphical elements (Wickens and Andre, 1990), or perhaps augmenting graphical forms with digital values (Hansen, 1991). Bennett et al. (in press) discuss these possibilities in greater detail.

Task proximity and real-world tasks. A final criticism of the display proximity principle is that the construct of task proximity is not representative of real-world tasks. Originally fault detection was characterized as a high-proximity task and diagnosis was characterized as a low-proximity task. However, in normal operational systems detection and diagnosis are not so distinct. In the process of completing tasks in more complex domains, an observer will be required to consider the system from many different levels of abstraction, and it is a characteristic of performance that an observer must alternate between levels (Rasmussen, 1986). Another way of stating this is that there are multiple, interleaved task situations in real-world domains: Some decisions must be based on higher-level constraints, some decisions must be based on the values of individual variables (low-level data), and these two types of decisions are intermingled throughout the course of completing domain tasks such as detection and diagnosis.

Semantic Mapping Principle

The semantic mapping principle states that displays should be designed so that there is a "one-to-one mapping between the invisible, abstract properties of the process and the cues or signs provided by the interface" (Rasmussen and Vicente, 1989, p. 530). This alternative perspective focuses on the nature of meaning within a task context and seeks representations that provide one-to-one mappings to constraints (at all levels of abstraction) within the work space (Flach and Vicente, 1989).

This approach has an intuitive link to Gibson's ecological optics (1979), which argues that skilled performance is possible when the geometry of optical flow fields is specific to properties of surfaces and movements of an observer. In this approach display design is viewed as a challenge to support skilled performance by building display geometries that are specific to functional properties within work domains. Making the process constraints visible is the challenge. In designing displays to facilitate performance at divided attention tasks, the critical factor is the mapping between these emergent features and the semantics inherent to the domain. That is, how well do the emergent features produced by the display geometry correspond to the constraints of the task domain? If the display produces highly salient emergent features and these emergent features directly reflect the critical data relationships and inherent constraints in the domain, then improved performance is likely to follow. There is also a natural link to Gentner's (1983) concept of structure mapping as a key aspect in the use of analogical reasoning. A good analogy is one in which the relational structure of the base domain (that which is understood) maps to critical relational structures in the target domain (that which is to be understood).

The importance of mapping has been recognized in the visual attention literature. Pomerantz and Pristach (1989), wrote, "the performance characteristics of configural dimensions will not surface unless (a) the stimuli contain emergent features *and* (b) those emergent features are distributed among stimuli in a way that they are useful to the subject in performing assigned tasks" (p. 646).

Whereas the proximity compatibility approach focuses primarily on visual form (configural vs. separable form), the semantic mapping approach focuses on what Woods (1991) refers to as *representational form.* With this approach the display is seen as "a referential medium where visual (and other elements) are signs or tokens that function within a symbol system" (p. 174). The display must be evaluated in terms of how these tokens map onto the functional properties of the process that is being represented. Woods (1991) uses the term *analogical integration* to describe displays that use configural geometries to accomplish the semantic mapping. He writes that "in analogical representation *the structure and behavior of the representation (symbol) is related to the structure and behaviour of what is being represented (referent).* This means that perceptions about the form of representation correspond to judgments about the underlying semantics" (p. 185).

Practical guidelines. Here is a list of three practical guidelines by which the semantic mapping principle might be applied to graphic design:

(1) Each relevant process variable should be represented by a distinct element within the display. If precise information about this variable is desirable, then a reference scale or supplemental digital information should be provided.

(2) The display elements should be organized so that the emergent properties (primarily

symmetries) that arise from their interaction correspond to higher-order constraints within the process. Thus when process constraints are broken (i.e., a fault occurs), the corresponding geometric constraints are also broken (the display symmetry is broken).

(3) The symmetries within the display should be nested (from global to local) in a way that reflects the hierarchical structure of the process. High-order process constraints (e.g., at the level of functional purpose or abstract function) should be reflected in global display symmetries; lower-order process constraints (e.g., functional organization) should be reflected in local display symmetries.

SUMMARY

Early research in display design has framed the problem in terms of divided and focused attention. It was observed that an explosion of data has occurred with the increasing complexity of systems. Object and configural displays were considered as solutions because they engaged the parallel processing capacities of human perceptual systems, thus allowing the observer to integrate large amounts of data with little attention cost. However, attention is not the only (and perhaps not even the most important) concern. As Woods and Roth (1988) noted, the problem in complex systems is both too much data and too little information. The problem is one of meaning or understanding. In complex systems the function of displays is to provide information in support of problem solving. The display must specify the constraints that govern the process being monitored. The state variables have meaning only in the context of these constraints. The review of research indicates that configural displays provide an opportunity to reduce both divided and focused attention demands. More important, however, configural displays provide an opportunity to turn data into information by presenting those data in a context that reflects the process constraints. See Vicente and Rasmussen (1990) for an example of how this mapping might be accomplished. Also see Beltracchi (1987) for an example of a configural display for thermodynamic processes.

Research to this point has concentrated almost exclusively on display syntax (i.e., visual form) and human attentional limitations. Future studies should direct more attention to display semantics (i.e., representational form) and to human problem solving. Both in designing research and in designing displays, more consideration should be given to basic research on problem solving and problem representation (e.g., Gentner and Stevens, 1983).

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