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Emergent Features and Perceptual Objects: A Reexamination of Fundamental Principles in Display Design

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**EMEGENT FEATURES AND PERCEPTUAL OBJECTS: A REEXAMINATION
OF FUNDAMENTAL PRINCIPLES IN DISPLAY DESIGN**

A thesis submitted in partial fulfillment of the
requirements for the degree of
Master of Science

BY

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GRADUATE SCHOOL

JANUARY 15TH, 2013

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Jerred Holt ENTITLED Emergent Features and Perceptual Objects: A Reexamination of Fundamental Principles in Display Design BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

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Objective: Our purpose was to discuss alternative principles of design (emergent features and perceptual objects) for analogical visual displays, to evaluate the utility of four different displays for a system state identification task, and to compare outcomes to predictions derived from the design principles. **Background:** An interpretation of previous empirical findings for three displays (bar graph, polar graphic, alpha-numeric) is provided from an emergent features perspective. A fourth display (configural coordinate) was designed to leverage powerful perception-action skills using principles of cognitive systems engineering / ecological interface design (i.e., direct perception). **Methods:** An experiment was conducted to evaluate these four displays. Primary dependent variables were accuracy and latency. **Results:** Numerous significant effects were obtained and a clear rank ordering of performance emerged (from best to worst): configural coordinate, bar graph, alpha-numeric, polar graphic. **Conclusions:** The findings are difficult to reconcile with principles of design based on perceptual objects but perfectly consistent with principles based on emergent features. Limitations of the most effective configural coordinate display are discussed and a redesign is provided to address them. **Applications:** The principles of ecological interface design that are described here (i.e., the quality of very specific mappings between domain, display, and observer constraints) are applicable to the design of all forms of displays for all work domains.

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INTRODUCTION

The combination of powerful, inexpensive graphics technology and our exquisite capability to process graphical information provide the very real potential for system designers to develop effective computerized decision making and problem solving support. Geometrical form displays (e.g., bar graphs) can be used to collect and summarize quantitative information about variables and relationships in a work domain. The term “analogical” has been used to describe these displays (Bennett and Flach 2011), since they simultaneously provide visual analogies of a work domain and also possess qualities that are analogical in nature (i.e., dynamic changes in the work domain produce corresponding changes in visual appearance).

Principles of design for analogical formats were first proposed in the mid 1980’s, with the increased availability of hardware technologies capable of providing real-time graphical images. The capability to create dynamic graphical images freed designers from the constraints associated with mechanical display instruments. Since that time, the opportunities afforded by this technology have been the focus of a substantial amount of research to explore how the graphical capabilities could facilitate human problem solving and decision making in complex control tasks (e.g., aviation –glass cockpits; and process control-integrated safety parameter display systems). Issues in the design of analogical

displays have centered on benefits and costs for different types of tasks and information needs. At the most fundamental level, these differences can be conceptualized as the need

to perform both focused attention tasks (i.e., obtain information about individual variables) and divided attention tasks (i.e., obtain information about relationships between variables, properties, and goals).

Although this literature has addressed a variety of issues, the concept of a perceptual object and its role in these design principles has tended to polarize researchers. Early design principles (e.g., Boles and Wickens 1987, Carswell and Wickens 1987) incorporated perceptual objects as a key factor. Displays that combined multiple variables into a single geometrical form were referred to as “object” displays. Benefits for divided attention tasks were predicted, based on the parallel, holistic processing of the perceptual object. Costs for focused attention tasks were predicted, based on the need to “unbind” or “unglue” parts of the perceptual object. Although these straight-forward principles and predictions have been modified and refined (e.g., Wickens and Carswell 1995), the construct of ‘perceptual object’ in which component features are processed in parallel still plays a central role.

Alternative principles have been proposed (Sanderson, Flach et al. 1989, Buttigieg and Sanderson 1991, Bennett and Flach 1992) based on the concept of “emergent features” (e.g., Pomerantz 1986, Pomerantz and Pristach 1989). Emergent features are higher-order visual properties (e.g., the relative heights of two adjacent bar graphs) that are produced by the interaction of lower-level graphical elements (e.g., the bar graphs). The emergent features perspective attributes improvements in divided attention tasks to an ability to focus in on a single emergent feature that specifies the ‘integral’ relation among the component’s variables needed for a decision. This approach suggests that the availability of the emergent feature does not necessarily interfere with

the ability to switch attention to component features. This suggests the possibility that there is not a necessary design trade-off between supporting divided and focused attention tasks. It suggests the possibility of a ‘configural’ graphical organization that might be equally effective in supporting focused and divided attention tasks (e.g., Bennett & Flach, 1992).

The emergent feature perspective predicts that the success or failure of a configural display will depend upon the quality of very specific mappings between the task or problem being solved (the need to isolated specific variables or to integrate across multiple variables) and the visual prominence of the associated graphical elements. If the emergent features are salient (i.e., if they are consistent with the constraints of the human visual system and can be picked up easily) and if they reflect critical aspects of the task (i.e., they are also consistent with the constraints of the work domain) then performance will be enhanced. This approach has subsequently been refined and broadened (e.g., Bennett and Walters, 2001; Reising and Sanderson, 2002; Bennett, Nagy et al. 2012); it is now an integral part of the cognitive systems engineering and ecological interface design (CSE, EID) framework (Rasmussen, Pejtersen et al. 1994, Vicente 1999, Bennett and Flach 2011). Framed within a triadic semiotic system, the EID framework emphasizes that the ultimate limits to human performance rest with the mapping of deep structure within the problem (i.e., the ecology), to graphical structures in a display (e.g., configural geometries), to salient properties of the perceptual field (i.e., fitting well with appropriate mental schema of the task).

In the present study we revisit fundamental issues in the design of analogical visual displays to support performance at divided attention tasks. Bennett and Flach’s

(1992) review of early laboratory findings revealed two studies where a non-object display produced significantly better performance than an object display. The Sanderson et al., (1989) study was designed and interpreted from the triadic perspective. Here we explore the results of the second study (Coury, Boulette et al. 1989) from the triadic perspective and attempt to replicate their findings with some minor variations in methodology. We also illustrate the principles and utility of the triadic approach more fully by designing and evaluating a new geometrical form display.

The divided attention task used in the Coury et al. study is a laboratory version of a critical task found in more complex systems: the identification of system state. This simple system has four variables (Q, M, B, and H); the relationships between these variables define one of four alternative system states (see Table 1). The participant is presented with a static display containing the four variables and is required to indicate the appropriate system state.

Table 1. System states defined by ranges of values for system variables

System	System Variable			
State	Q	M	B	H
1	25-51	49-75	0-26	74-100
2	25-51	49-75	74-100	0-26
3	49-75	25-51	0-26	74-100
4	49-75	25-51	74-100	0-26

Bar graph display. Coury et al. (1989) found that a bar graph display (i.e., a non-object display) generally produced the best performance. The heights of individual bar graphs are low-level emergent features; they configure to produce higher order emergent features: the relative heights of two adjacent bar graphs (see the dashed lines in Figure 1a). Previous research has indicated that observers are particularly sensitive to this visual information (e.g., Cleveland 1985, Sanderson, Flach et al. 1989). Thus, the quality of the mappings between display and human observer appears to be high: the emergent features produced by the display are salient and can be picked up easily.

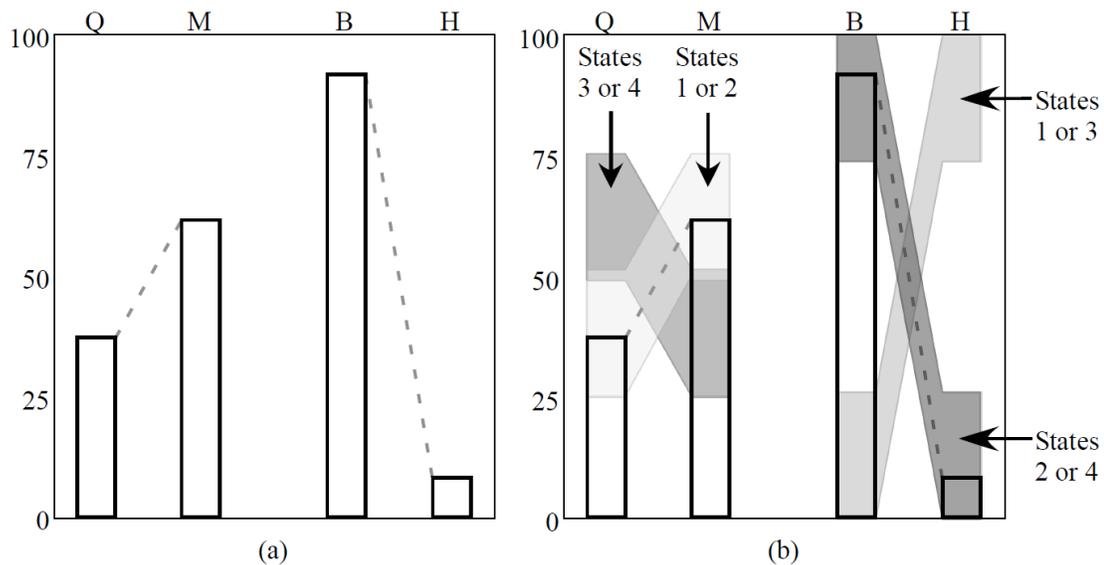


Figure 1. The bar graph display. A. The higher order emergent features are the relative heights of adjacent bar graphs (emphasized by the dashed lines). B. The rules for state identification listed in Table 1 are represented graphically; there is a relatively direct mapping between these domain constraints and the emergent features in the display. (Adapted with permission from Bennett, K. B., and Flach, J. M., Display and interface design: Subtle science, exact art. Copyright 2011 by CRC Press. All rights reserved.)

The second set of mappings is also effective. Figure 1b illustrates how these emergent features provide accurate reflections of underlying task constraints. The rules for state identification listed in Table 1 are represented graphically by the shaded areas in Figure 1b. It is readily apparent that two comparisons must be made between two pairs of variables (i.e., Q vs. M and B vs. H). In Figure 1b the relationship between Q and M falls in the shaded area corresponding to State 1 or 2 (thereby eliminating States 3 and 4). The relationship between B and H falls in the shaded area corresponding to State 2 or 4. This eliminates State 1 and specifies State 2 as the correct response. Thus, the constraints of the task are specified in a reasonably direct fashion by salient emergent features: the relative heights of the pairs of bar graphs provide a direct visual analogy to the rules for state identification. Performance is effective with this display because the emergent features are well-mapped to both domain and observer constraints.

Polar graphic display. In this display (see Figure 2a) each variable is placed on a coordinate axis and adjacent variables are connected with contour lines to produce a four-sided polygon. The polar display produces a far greater variety of emergent features than the bar graph display. Listed in order of increasing salience, these hierarchically nested emergent features are: spatial extent (individual variables located on an axis), line orientation (lines connecting pairs of contiguous variables), angle and shape (configurations between two lines that connect three contiguous variables, e.g., “spike” vs. “flat”) and overall shape of the geometric form (symmetry and balance). Thus, the polar display produces a rich set of hierarchically-nested and increasingly salient emergent features that can be picked-up easily by the observer. However, Coury et al.

found that this display often produced significantly worse performance for state identification than the bar graph.

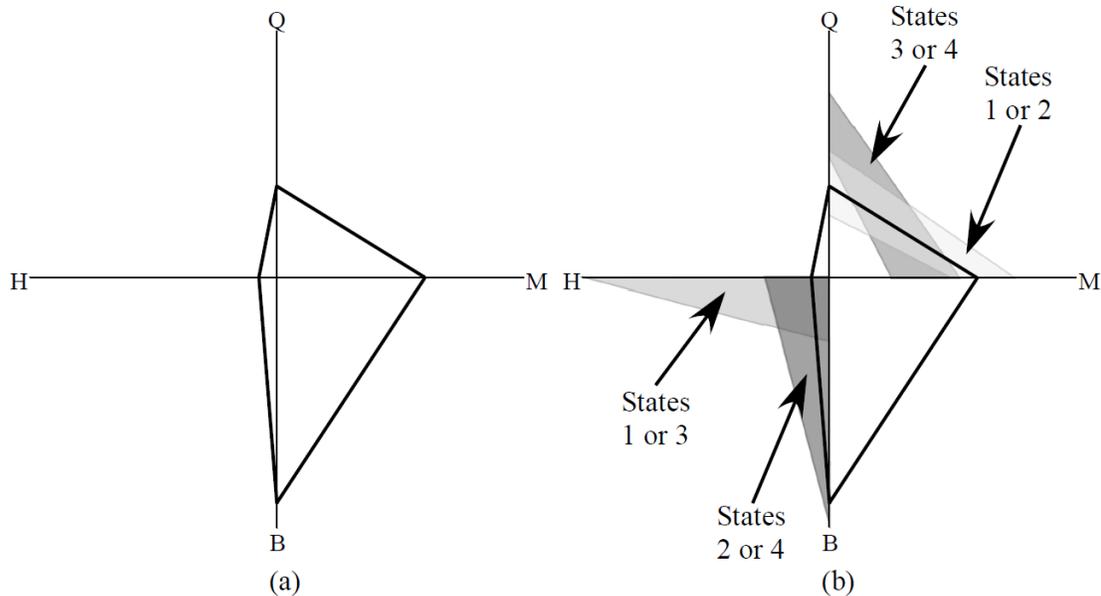


Figure 2. The polar graphic display. A. A wide variety of emergent features are produced including linear extent, orientation, shape, angle, symmetry, balance (see text). B. The rules for state identification listed in Table 1 are represented graphically; there is an indirect mapping between these domain constraints and the emergent features in the display. (Adapted with permission from Bennett, K. B., and Flach, J. M., *Display and interface design: Subtle science, exact art*. Copyright 2011 by CRC Press. All rights reserved.)

One potential explanation lies in the fact that there are only two emergent features that specify task constraints directly: the orientation of the lines that connect a relevant pair of variables (Q-M and B-H, see the shaded areas that represent the classification rules in Figure 2b). All of the other emergent features described above are meaningless,

yet difficult to ignore. This could have a negative impact on performance (e.g., Bennett and Fritz 2005, Bennett and Flach 2011). Second, the changes in the orientation of the Q-M contour line that specify different system states can be quite small and therefore difficult to detect. Thus, the two sets of mappings described earlier are ineffective: the visual constraints introduced by the display are not well-mapped to either domain or observer constraints.

Alpha-numeric display. Coury et al. (1989) evaluated a third display consisting of a textual label and digital value for each variable. These “propositional” (Woods 1997, Bennett and Flach 2011) representations have no analogical visual properties and do not support direct perception. Relationships between variables must be mentally calculated to perform divided attention tasks like state identification (e.g., Bennett and Walters 2001). Coury et al. found that performance with the alpha-numeric display was significantly worse than performance with the bar graph display and roughly equivalent to that obtained with the polar graphic display.

Configural coordinate display. Figure 3 illustrates an alternative display designed from the CSE / EID perspective to provide a more direct mapping between geometrical, perceptual, and domain constraints. A single point is calculated to simultaneously capture differences between each pair of relevant variables. The x coordinate of the point is obtained by subtracting the value of H from the value of B; its y coordinate is obtained by subtracting Q from M. The axes are arranged so that one very salient emergent feature (i.e., the spatial location of this point in one of the four quadrants) directly specifies correct system state (see the state labels and shaded areas in Figure 3). This display represents domain constraints (i.e., comparisons between pairs of

variables) in a very direct fashion (spatial location of the point) that is likely to be picked up very easily by an observer.

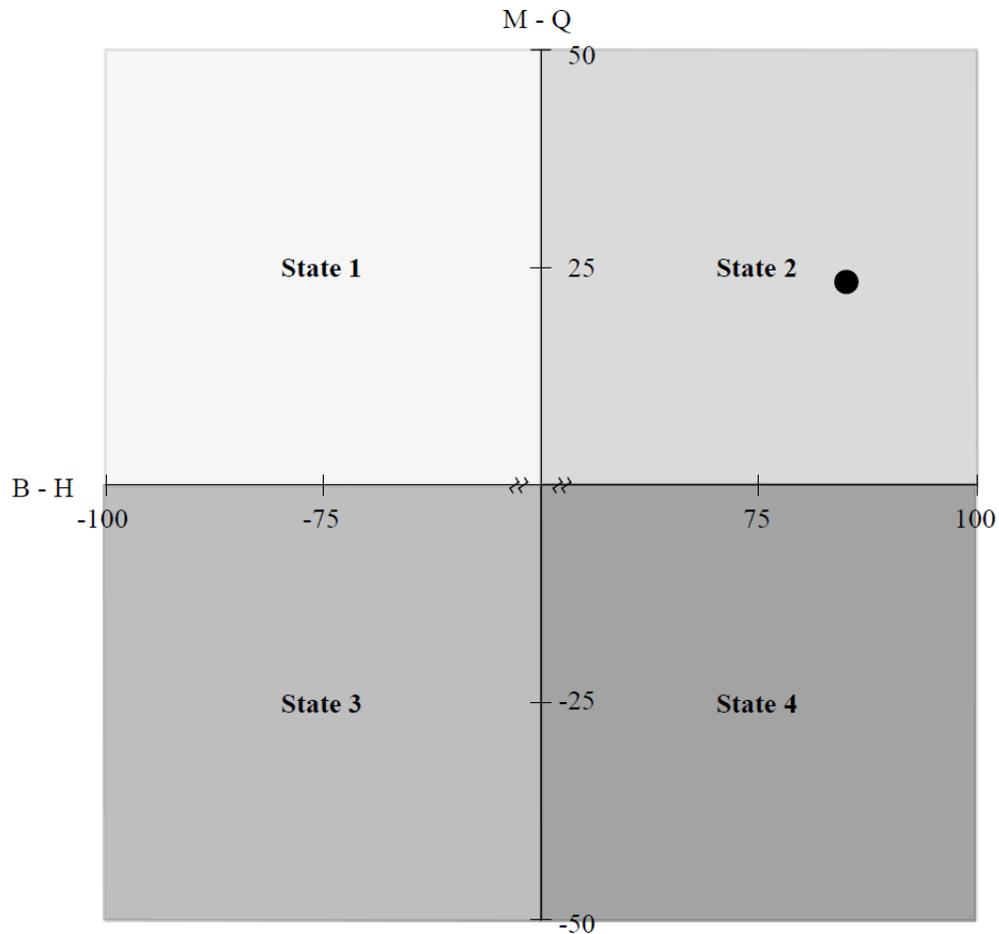


Figure 3. A configural coordinate display illustrating relationships between variables and system states. The critical differences between pairs of variables are used to determine the x and y coordinates of the point; the spatial location of this point in the coordinate grid is an emergent feature that specifies system state (graphically represented by shading). (Adapted with permission from Bennett, K. B., and Flach, J. M., *Display and interface design: Subtle science, exact art*. Copyright 2011 by CRC Press. All rights reserved.)

A variation of the Coury et al. (1989) study was conducted with the majority of methodological details held constant. One major change involved training. Participants were required to learn system state boundaries via trial and error in the original study; in the present study participants were provided with explicit instructions about system states and how specific features of each display testified with regard to these states. Also, some minor modifications were applied to the format of the original displays to increase their consistency. One goal was to determine whether the pattern of results for the original three displays (polar graphic and alpha-numeric roughly equivalent; bar graph superior) would replicate. A second goal was to evaluate the effectiveness of the new configural coordinate display. It was predicted that this display would be most effective format due to the more direct mappings between display, perceptual, and domain constraints.

METHODS

Participants. Twenty four participants (10 male, 14 female) between the ages of 20 and 30 completed the experiment on a voluntary basis. Participants were recruited through email solicitation of graduate and undergraduate students at Wright State University and Washington of St. Louis University. All participants had normal or corrected to normal vision.

Stimuli

Data sets (i.e., specific values of four variables for a trial) were generated that varied the “uncertainty” of system state. As Table 1 and Figure 1 illustrate, there was an overlap region (49, 50, and 51) where the Q and M variables could simultaneously satisfy multiple system states. Eight levels of uncertainty were defined by varying the difference between these two variables in controlled ranges. The ranges for Levels 1 through 6 were 50-46, 45-38, 37-30, 29-22, 21-14 and 13-6. An additional requirement was that no values were in the overlap region. For example, values of 55 and 45 for Q and M are legitimate for Level 6 (difference of 10). The range for Level 9 was 5-1; one, but not both, of the variables also had to be located in the overlap region (e.g., 50 and 53). The range for Level 10 was 2-0 with both variables in the overlap region (e.g., 49 and 51). The difference between B and H values ranged from 50 to 100. Specific values for all four variables were chosen randomly within these range requirements. A total of 64 data

sets were developed by factorially combining uncertainty (8 levels), system state (4 levels), and repetition (2 levels).

The bar graph display in Coury et al. (1989) contained gridlines and labels while the polar graphic display did not. These features were added to the polar graphic to improve consistency. In addition, gray scale shading was added to both analogical displays. Figure 4 illustrates the four display formats used in the experiment.

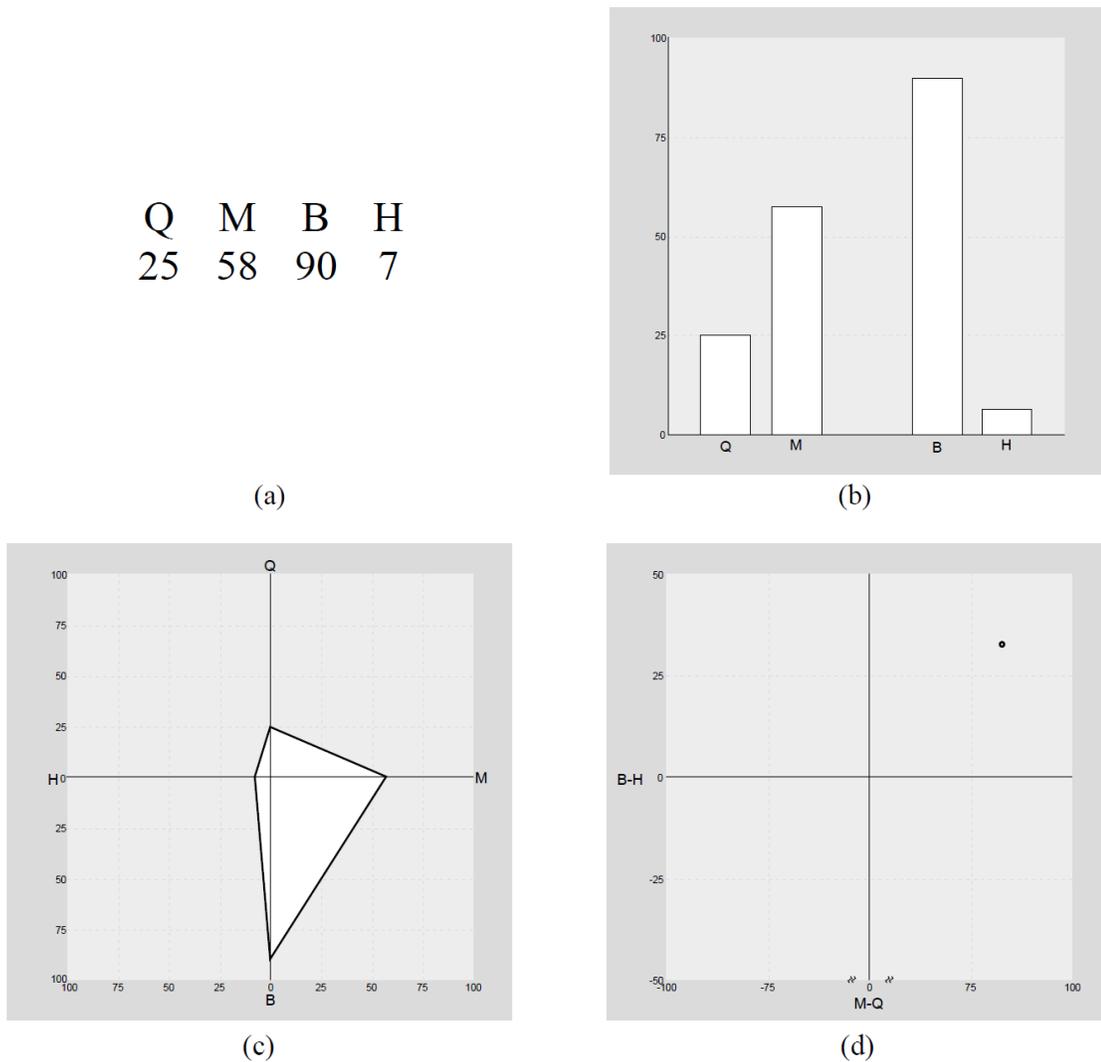


Figure 4. The visual appearance of the four displays evaluated in the present study. A. Alpha-numeric. B. Bar graph. C. Polar graphic. D. Configural coordinate. (Adapted with

permission from Coury, B. G., Boulette, M. D., and Smith, R. A., Effect of uncertainty and diagnosticity on classification of multidimensional data with integral and separable displays of system status. *Human Factors*, 31, 551-570. Copyright 1989 by the Human Factors and Ergonomics Society. All rights reserved.

Procedure

Training and experimental software packages were distributed digitally to participants. The PowerPoint training presentation (nineteen slides) provided comprehensive descriptions of the task (e.g., variables, critical relationships, system states, uncertainty), the displays (annotated graphical examples for each display, system state, and levels of uncertainty) and response requirements (general and specific, e.g., to respond as accurately and quickly as possible). These descriptions were purely objective and no specific response strategies were provided. The experimental software required a display resolution of 1024x768 and a refresh rate of 60 Hz to run.

Participants completed eight blocks of trials using a single display per block. Each display appeared once in the first four blocks; the order was counter-balanced across participants (and repeated in the second four blocks). The 64 data sets were used once for each display: 32 in the first block (chosen randomly, but balanced across 4 system states and 8 uncertainty levels); the remaining 32 in the second block (repetition). Presentation order of trials within a block was random. In summary, the experimental design contained 4 within-subjects factors: display (4), system state (4), uncertainty (8), and repetition (2).

Each of the first four blocks began with 5 practice trials. Participants initiated a trial by pressing a key. A display appeared and remained visible until an appropriate response (numbers 1-4) was entered on the keyboard. Feedback on the accuracy of the participant's response ("correct" or "incorrect" and the correct response) was provided. Latency was measured from the time that a display appeared on the screen until a response key was pressed (1/60th of a second accuracy). Accuracy scores (1 or 0) were obtained by comparing actual and reported system state. Note that when system state was ambiguous (i.e., the Q-M relationship did not rule out any system states) both of the two states specified by the B-H relationship were counted as a correct response.

RESULTS

Tests for outliers (Lovie 1986, pp. 55-56) were conducted on latency scores: $T1 = (x(n) - \bar{x}) / s$, where $x(n)$ is a particular observation (one of n observations), \bar{x} is the mean of those observations, and s is the standard deviation of those observations. Ninety two of 6144 scores (1.5%) were identified as outliers and removed from subsequent analyses (corresponding accuracy scores were also removed). Preliminary analyses indicated that system state had no significant impact on performance and raw scores were averaged across this variable.

Latency. A 4 (display) X 8 (uncertainty) X 2 (repetition) within-subjects repeated measures ANOVA was performed. The main effects of display ($F(3,69)=35.25$; $p<.000001$), uncertainty ($F(7,161)=21.74$; $p<.000001$), and repetition ($F(1,23)=5.53$; $p<.03$) were significant. Figure 5 illustrates the combined average performance for each display across latency and accuracy. The display x uncertainty interaction effect was significant ($F(21,483)=3.92$; $p<.000001$); the associated means are illustrated in Figure 6.

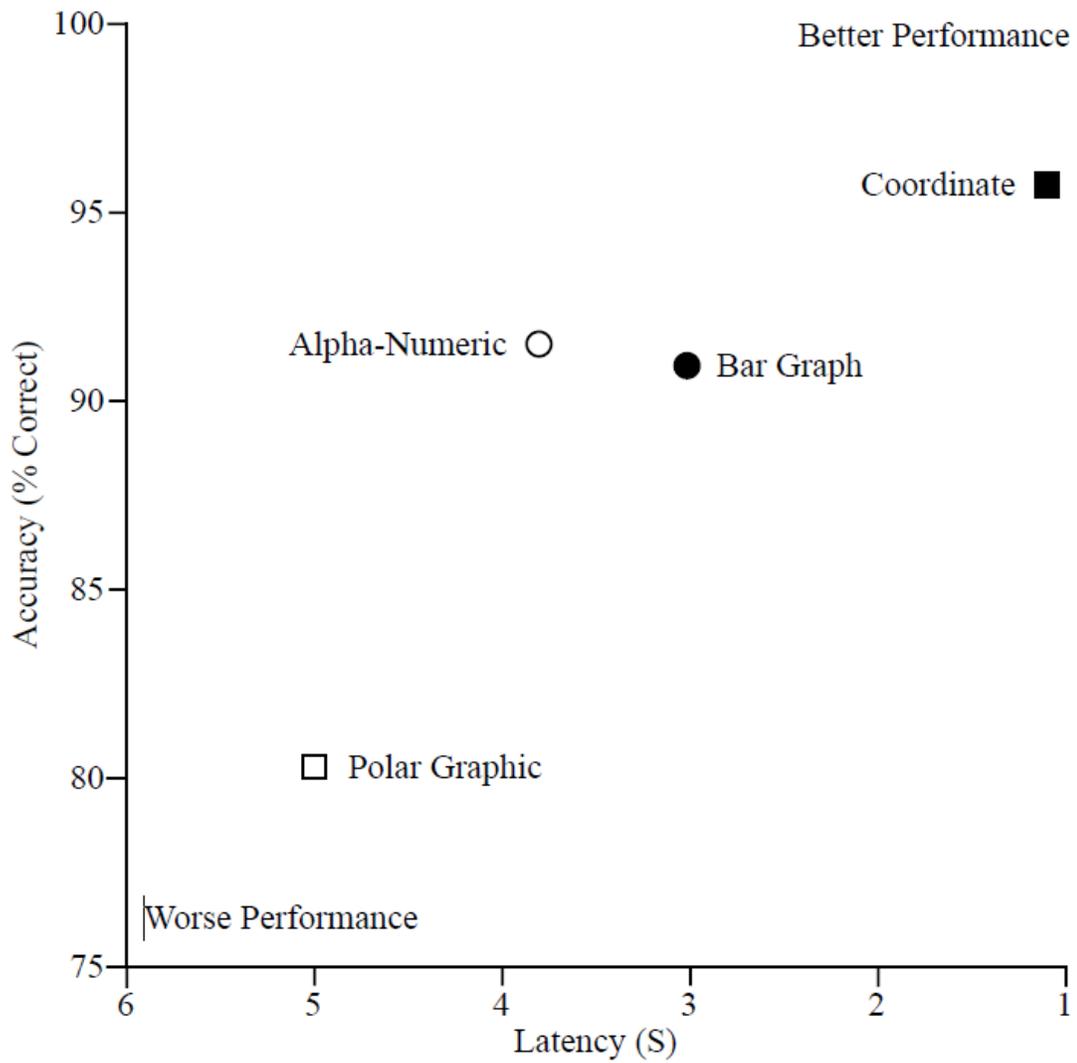


Figure 5. Average accuracy and latency scores for the significant main effects of display.

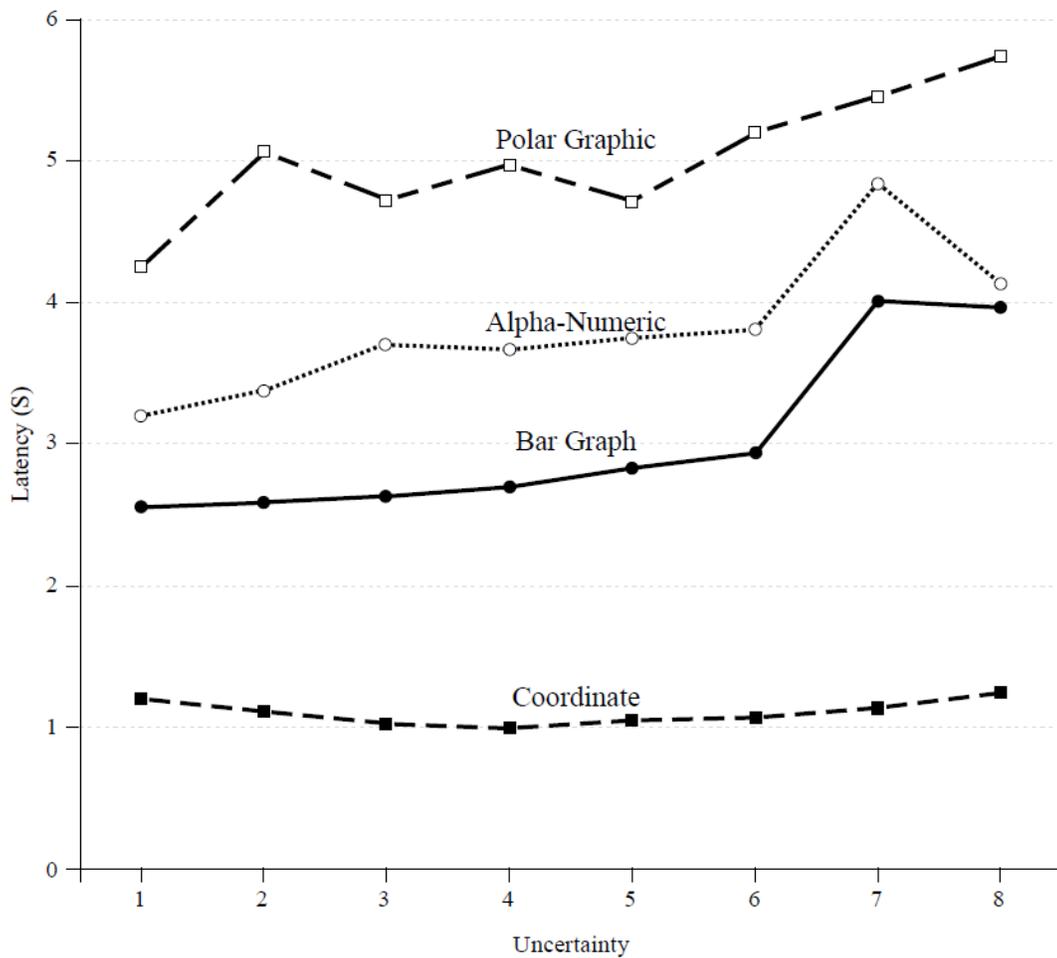


Figure 6. Average latency scores for the significant display by uncertainty interaction effect.

Accuracy. A 4 (display) X 8 (uncertainty) X 2 (repetition) within-subjects repeated measures ANOVA was performed. The main effects of display $F(3,69)=24.04$; $p<.000001$) and level of uncertainty ($F(7,161)=13.40$; $p<.000001$) were significant, as well as the interaction between them ($F(21,483)=3.72$; $p<.000001$). No other effects were

significant. Figure 5 illustrates average latency performance by display; the average accuracy performance for the display by uncertainty interaction effect is illustrated in Figure 7. Note the finding of increased accuracy at the highest level of uncertainty. This counterintuitive finding was caused by the fact that multiple responses were counted as correct (due to ambiguity in system state).

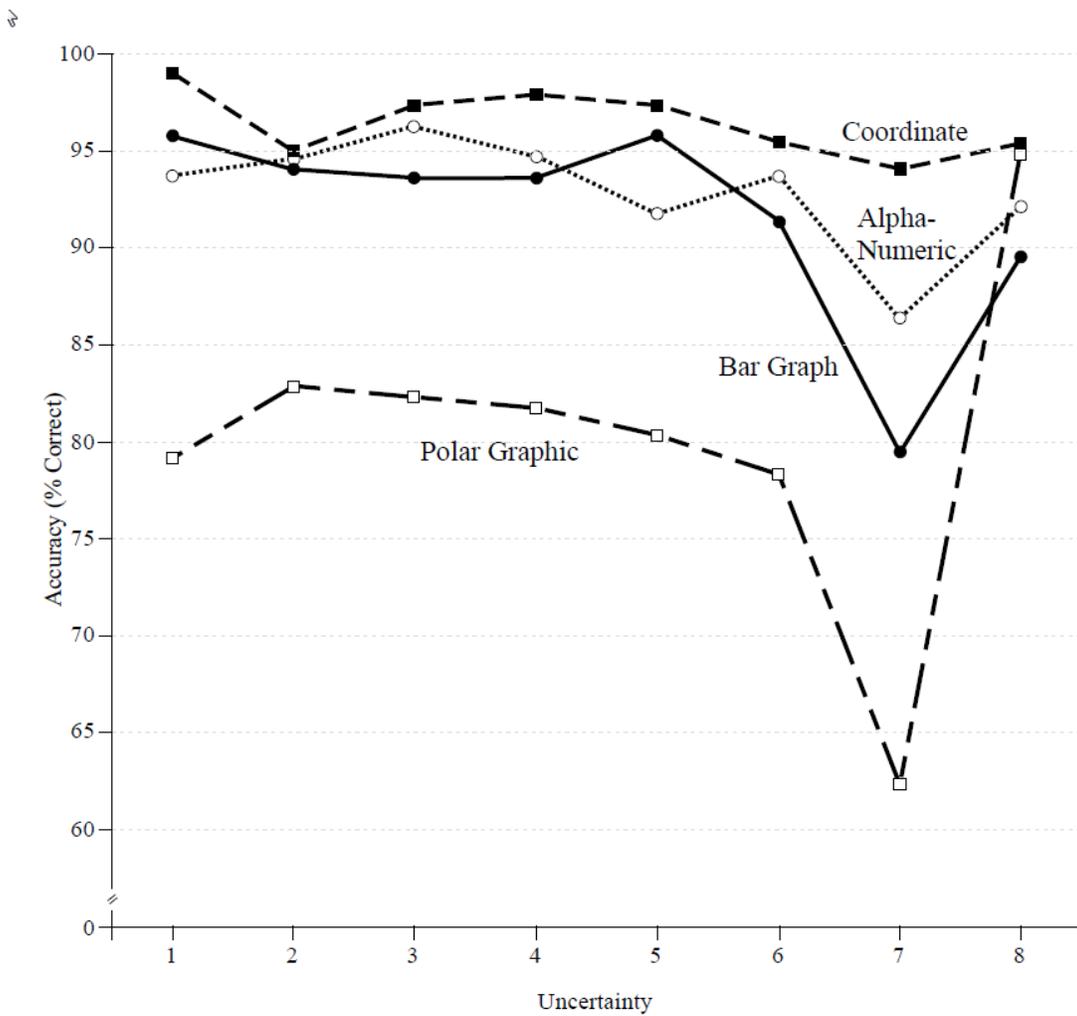


Figure 7. Average accuracy scores for the significant display by uncertainty interaction effect.

Contrasts were conducted to compare mean levels of performance between displays for the simple main effects of display at each level of uncertainty. The results for both accuracy and latency are presented in Figure 8, which uses the following symbology. Each display is represented as an icon; the left-to-right ordering of icons represents progressively poorer average performance. Each contrast between two displays is represented by the underscore line between two icons. A dark line indicates that the contrast was statistically significant ($F(1, 23); p < 0.05$).

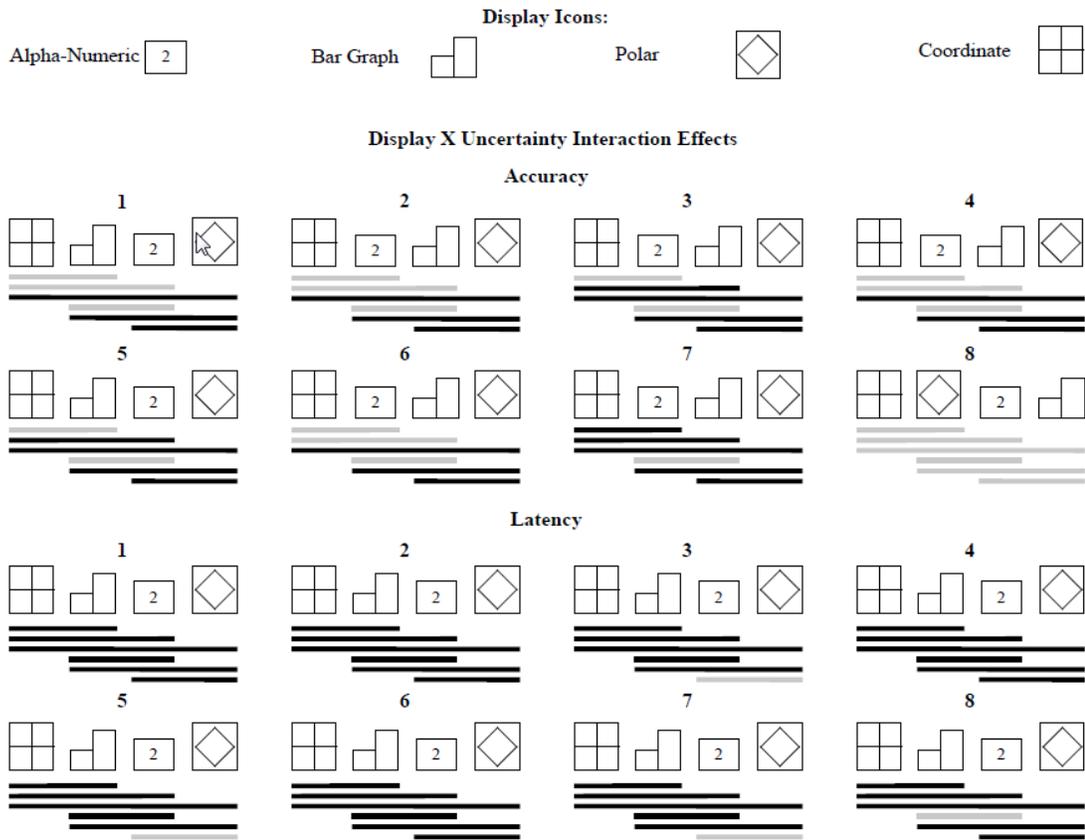


Figure 8. Graphical summary of contrasts for the simple main effects of display at each level of uncertainty. Display icons are ordered from right to left in increasing levels of average performance. Individual contrasts are represented by an underscore line spanning two display icons; statistical significance at the .05 level is represented by a dark underscore.

DISCUSSION

We begin by considering the overall pattern of results for the three displays originally investigated by Coury et al. (1989). A clear rank ordering was obtained (from best to worst): bar graph, alpha-numeric, and polar graphic (see Figures 5, 6 and 7). These performance differences will be summarized in terms of the interaction contrasts (see Figure 8). The bar graph display was decisively better than the polar graphic display for both accuracy and latency: 15 of the 16 interaction contrasts between these two displays were significant. The bar graph display was also decisively better than the alpha-numeric display for latency (7 of 8 contrasts were significant). However, there were no significant differences between these displays for the accuracy of responses. Finally, the alpha-numeric display was decisively more effective than the polar graphic display for accuracy (7 of 8 contrasts were significant) and predominately more effective for latency (5 of 8 contrasts were significant).

The bar graph was the most effective of these three displays because it produces a limited number of salient emergent features that are also well mapped to task constraints, as described in the introduction. Essentially participants needed to learn how to categorize four distinctive graphical patterns into the four system states. Using a slash mark to represent the relevant emergent feature (i.e., relative height of two bar graphs), these four patterns are: State 1 (/ /), State 2 (/ \), State 3 (\ /), and State 4 (\ \). These emergent features, in combination with knowledge about how the visual patterns testify

with regard to system state, transform a potentially difficult and cognitively demanding task into a largely perceptual task.

An intermediate level of performance was obtained with the alpha-numeric display. It is likely that participants developed cognitive strategies to compensate for the lack of analogical visual properties. For example, one strategy would be to mentally calculate the numerical differences between variables and then assign a verbal code (e.g., “low-high, low-high”) that is the functional equivalent of the visual patterns described above. The results obtained for the alpha-numeric and bar graph displays fit a pattern of performance that is consistent with this interpretation. The verbal code would be equally as precise as the visual patterns produced by the bar graph; no significant differences in accuracy were obtained. However, these mental computations would also increase the amount of time required to produce a response, relative to simply perceiving the patterns; significant differences in latency were obtained.

The polar graphic produced the poorest performance of all displays. Two interpretations were provided in the introduction: a) numerous and salient emergent features that were not relevant to the task and b) emergent features that were critical to the task, but not particularly salient. An analysis of the display geometries revealed some evidence in support of the second interpretation. Differences in system state could be specified by differences in the orientation of the Q-M contour line that were as small as approximately $\frac{1}{2}^\circ$. This is a value that approaches perceptual limits (e.g., Orban, Vandebussche et al. 1984). Thus, it is likely that the polar graphic display produced poor performance because its display geometries required visual discriminations that were far too subtle to be performed reliably.

In summary, our reevaluation of these three displays revealed a pattern of results that was reasonably consistent with, but more decisive, than those of Coury et al. (1989). We found overall performance advantages for the bar graph display that were more consistent and more pronounced. We found clear evidence that performance with the alpha-numeric display was superior to the polar graphic display (as opposed to being roughly equivalent). These differences are probably due to the comprehensive training on the task, variables, system states and displays that was provided in our study. This allowed participants to spend less time discovering basic knowledge about the task and more time honing their skills and strategies. These findings are probably more representative of skilled performance with these displays.

The new configural coordinate display, designed from the CSE / EID perspective, produced the best overall performance of all displays (see Figure 5). This was particularly true for the latency of responses (all comparisons with all other displays were statistically significant) although there were many results favoring accuracy as well. The performance advantages for the coordinate display are particularly evident when uncertainty is considered. Increases in uncertainty produced fairly systematic degradation of performance for all other displays (see Figures 6 and 7), particularly for uncertainty level 7. In contrast, performance with the coordinate display was essentially impervious to changes in uncertainty.

The design goal of direct perception was realized in the configural coordinate display: the geometrical constraints it provides map directly into both work domain and perceptual constraints. Specifically, the spatial location of a single point in the coordinate grid provides a salient emergent feature that accurately reflects the rules for state

identification and requires little or no mental calculations, nor any sort of fine perceptual discriminations. As a result, this display achieves the primary goal of ecological interface design: a tight coupling between human, machine, and domain which eliminates cognitive demands and leverages the powerful perceptual capabilities of the human.

General Discussion

The configural coordinate display also has some obvious limitations. In complex, dynamic work domains displays must also be designed to support focused attention tasks: an understanding of how individual variables contribute to higher order properties is essential in determining appropriate control input. The coordinate display fails miserably in this regard. It is “integral” in the sense that the term was originally conceived in the visual perception literature: the ways in which the individual variables contribute to overall system state are completely hidden in this representation. In other words, the salience of the higher order relations was obtained at the cost of occluding the contribution of component variables.

Figure 9 illustrates a redesign of the coordinate display to address these concerns. The essential features of the original design are retained. The horizontal axis for the B and H variables has been expanded to include the full range of values. Bar graphs (and digital values) for individual variables were added to support performance at focused attention tasks. The location of the axes for both sets of bar graphs are dynamic. The tops of the H and Q bar graphs are always aligned with the origin of the appropriate axis in the coordinate display. The value of these variables therefore determine where the origin of each bar graph axis will be located. Furthermore, this geometrical layout ensures that the

tops of the B and M bar graphs specify the x and y coordinates of the point directly, as the dashed lines in Figure 9 make explicit.

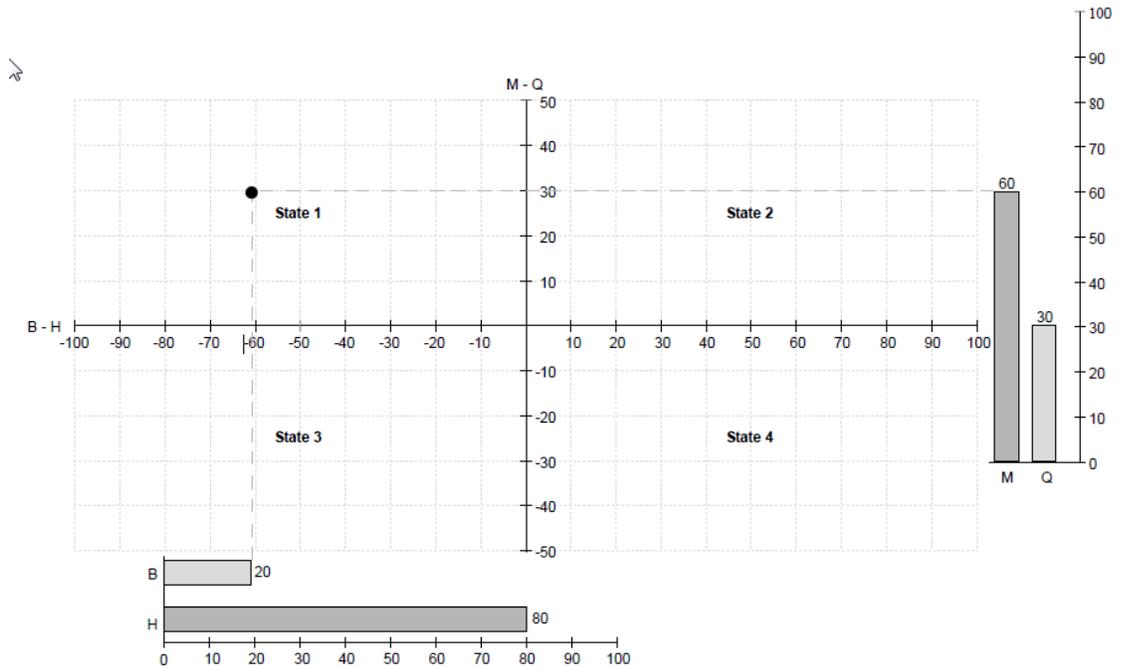


Figure 9. A redesign of the configural coordinate display to support performance at focused attention tasks.

This redesign provides analogical representations that directly (and simultaneously) specify the value of individual variables (i.e., horizontal or vertical extent of individual bar graphs), critical relationships between them (i.e., relative heights or widths between the bar graphs of a relevant pair), and overall system state (i.e., spatial location of the point in a display quadrant). Thus, the design goal of a single, integrated display that is capable of supporting the observer in meeting task demands along the divided-focused continuum has been achieved. Furthermore, these integrated analogical representations provide a continuous graphical explanation of system dynamics.

Consistent with previous findings (Coury, Boulette et al. 1989, Sanderson, Flach et al. 1989), our results indicate that performance at a divided attention task (state identification) was poorest for the display that had the most object-like properties (i.e., the polar coordinate format). These results are difficult to reconcile with design principles based on perceptual objects, but perfectly consistent with the organizing principles of the triadic approach (see previous discussions). The results of the present study contribute to a growing literature suggesting that approaches that focus exclusively on the mapping between the form of the display (e.g., object or separable) and internal processing constraints (e.g., parallel or serial processing) can lead to misleading design recommendations.

In retrospect, it is easy to understand why researchers initially focused on the simple concept of perceptual objects as a design principle. Placing multiple variables into a single geometrical form without concern for work domain constraints will produce a wide variety of emergent features; some will be well-mapped to task constraints and others will not (e.g., the polar graphic display). The design principle of perceptual objects can appear to be successful, but only because observers are amazingly adept at determining which of those visual properties are relevant for the performance of particular tasks (and which are not). However, as Bennett and Fritz (2005, p. 137) observe, "... the guiding principles [of analog display design] have moved well beyond the simple strategy of throwing variables into a geometric object format and relying upon the human agent's powerful perceptual systems to carry the design."

Revisiting this early study of analog display design has served to make these guiding principles more explicit. Display and interface design is a surprisingly

complicated endeavor; the difficulty of getting a design right is grossly underestimated. No single display format is inherently better, or worse, than any other. The effectiveness of a display will be determined by very specific interactions between domain, display, and observer constraints. These interactions are complicated and difficult to predict, even for relatively simple tasks and displays like those in the current study. For real work domains these challenges are magnified tremendously. More complicated visual explanations that simultaneously span goals, functions, and physical resources will be needed to provide effective decision making and problem solving support. It is here that the concepts, analytical tools, and methodologies of the CSE and EID approaches become indispensable.

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