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The placement of digital values in configural displays

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Abstract

Investigations of the relative merits of graphical (analog) and numerical (digital) formats have a long tradition in the display design literature. These issues are re-examined for the design of configural displays (displays that map multiple individual variables into a single graphical format). Six displays that varied with regard to the presence, spatial location, and dynamic behavior of digital values were evaluated. Performance was assessed for two tasks that imposed different cognitive demands. The results indicate that the presence of digital values had a substantial and positive impact on performance. The results also indicate a display by task trade-off. Placing a digital value in a spatially dedicated location improves performance when the variable of interest is known before the display is accessed. On the other hand, providing a dynamic spatial link between graphical elements of the configural display and the digital value improves performance when the variable of interest is dependent upon data relationships. Design recommendations based on these findings and practical considerations are discussed.

Keywords: Graphical displays; Digital values; Configural displays; Alpha-numerics

1. Introduction

> If we are going to make a mark, it may as well be a meaningful one. The simplest—and most useful—meaningful mark is a digit [1, p. 296].

The presentation of quantitative information with either graphical (analog) or numerical (digital) formats has been examined extensively. A number of empirical studies and literature reviews have considered the effectiveness of these two formats and the various contextual circumstances that might lead to the recommendation of one format over the other [2–17]. Although this literature does reveal some inconsistencies [18,19] several conclusions appear to be warranted. These two display formats produce different types of errors when participants are required to provide quantitative estimates of displayed information. The errors associated with digital formats are less frequent but more variable than those associated with graphical displays [6,7,20].

1.1. Relative merits of graphical vs. numerical presentation

Additional issues become relevant when these two types of display formats are considered for interfaces designed to support decision making in complex, dynamic domains. Intuition, design principles, and research findings indicate that the best choice will depend on the nature of the task to be performed. Digital values are precise, and thus useful when exact values are required [3,6,7,19]. Hansen [9] suggests that this precision might be useful under several contexts, including when: (1) the value of state variables need to be communicated to others, (2) a system fault is present (e.g. to help determine the precise increase in flow that is required to compensate for a small leak), and (3) changes are small relative to the scale of the graphical representation.

In contrast, interfaces that provide only digital displays present difficulties for the completion of tasks that require more than the consideration of individual variables. Under these circumstances digital formats require the user to mentally represent the problem and to perform mental

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calculations or comparisons. As Bennett et al. [21, p. 691] observed: '…operators are required to engage in knowledge-based behaviors: they must rely upon internal models of system structure and function (and therefore use the limited capacity resources of working memory) to detect, diagnose, and correct faults. As a result, the potential for errors is increased dramatically.' In general terms, analog displays are more effective than digital displays when the task requires the consideration of relationships between variables, including trends, rate of change, general status of a variable, or comparisons between variables [3,12,16,19,22].

'Configural' displays are a particular type of analog format that has received a great deal of recent attention. Individual variables are arranged in spatial patterns (often connected with contour lines) to produce geometrical forms; the shapes of these forms vary as a function of changes in the value of these variables. An example of a configural display is shown in Fig. 1: the values of four individual variables are plotted; the intersection of these variables forms a rectangle. The salient, high-level visual properties that are produced (e.g. symmetry) are usually referred to as 'emergent features' [23]. For example, the display in Fig. 1 produces a number of emergent features including the area, width, and height of the rectangle.

A substantial body of laboratory research indicates that configural displays can be effective when the consideration of relationships between variables is essential to the completion of domain tasks [4]. The degree of success is determined by the quality of the mapping between the visual properties of the display and the physical, functional, and goal-related properties of the domain [21].

1.2. Issues in the annotation of configural displays with numerical values

As Hansen [9, p. 542] has observed, the long-standing tradition of comparing performance between analog and digital formats might be somewhat misguided: '…human factors researchers should not treat the discussion of graphical vs. analytical (e.g. numerical) interfaces as an either/or issue.' Existing hardware and software technology provides designers with sufficient flexibility to consider the combination of these display formats. From a theoretical perspective it is readily apparent that combined analog/numerical displays have the potential to support performance across a broad spectrum of task requirements.

This potential is supported by the findings of Bennett and Walters [3]. A number of alternative display design techniques (including digital values) were applied to a configural display. Performance was assessed for both basic information extraction tasks (i.e. quantitative estimates of a variable) and tasks that required the consideration of variable relationships and domain semantics (i.e. system control, fault detection). One display clearly produced the most effective performance when both categories of tasks were considered: an analog configural display that was annotated with digital values.

Thus, it appears that one important avenue for design is to consider how analog and digital formats might be combined most effectively. Achieving consistency in interface design has always been a fundamental concern and conventional wisdom dictates that digital values should be located in a dedicated spatial position. Bennett and Walters [3] followed conventional wisdom by placing the digital values in dedicated spatial positions located outside of the grid in which the configural display appeared. However, Hansen [9, p. 542] suggests an intriguing alternative, where digital values are placed '…with a spatial link to the corresponding graphical indication of the same data, moving with the dynamic graphics.' The present study investigated several versions of both design strategies.

1.3. Alternative placements of digital values in a configural display

Six versions of a configural display that varied with regard to the presence, spatial location, and dynamic behavior of digital values (Fig. 1) were evaluated. Five displays contained the same configural display and the same digital values (values for four system variables). The digital values were located in non-changing or 'static' spatial locations in two displays. The 'static axis' display (Fig. 1(a)) incorporated digital values that were located in the center of the two axes (on top of, or to the right of the display grid). The 'static bar' display (Fig. 1(b)) incorporated digital values that were located next to the associated bar graph (below, or to the left of the associated bar).

The spatial location of the digital values was dynamic in three displays (i.e. changing as a function of the associated variable). The 'dynamic axis' display (Fig. 1(c)) incorporated digital values that were anchored to end of the lines that extended from the configural display to the display axes. The 'dynamic bar' display (Fig. 1(d)) incorporated digital values that were anchored to the end of the appropriate bar graphs. The 'digital configural' display (Fig. 1(e)) incorporated digital values that were anchored to the side of the rectangle (centered and outside). Finally, the 'analog configural' display (Fig. 1(f)), did not incorporate any digital values.

1.4. Alternative evaluative contexts

The utility of these alternative placements was evaluated in two experimental contexts that simulated different types of demands associated with the use of digital values. The basic experimental task remained the same in both contexts: to provide a quantitative numerical value for one of the four variables presented in the display. The first context simulates a common scenario where the variable of interest is known before the display is accessed. The experimental prompt provided the name of the variable to be reported in this task; it will therefore be referred to as the 'name' task.

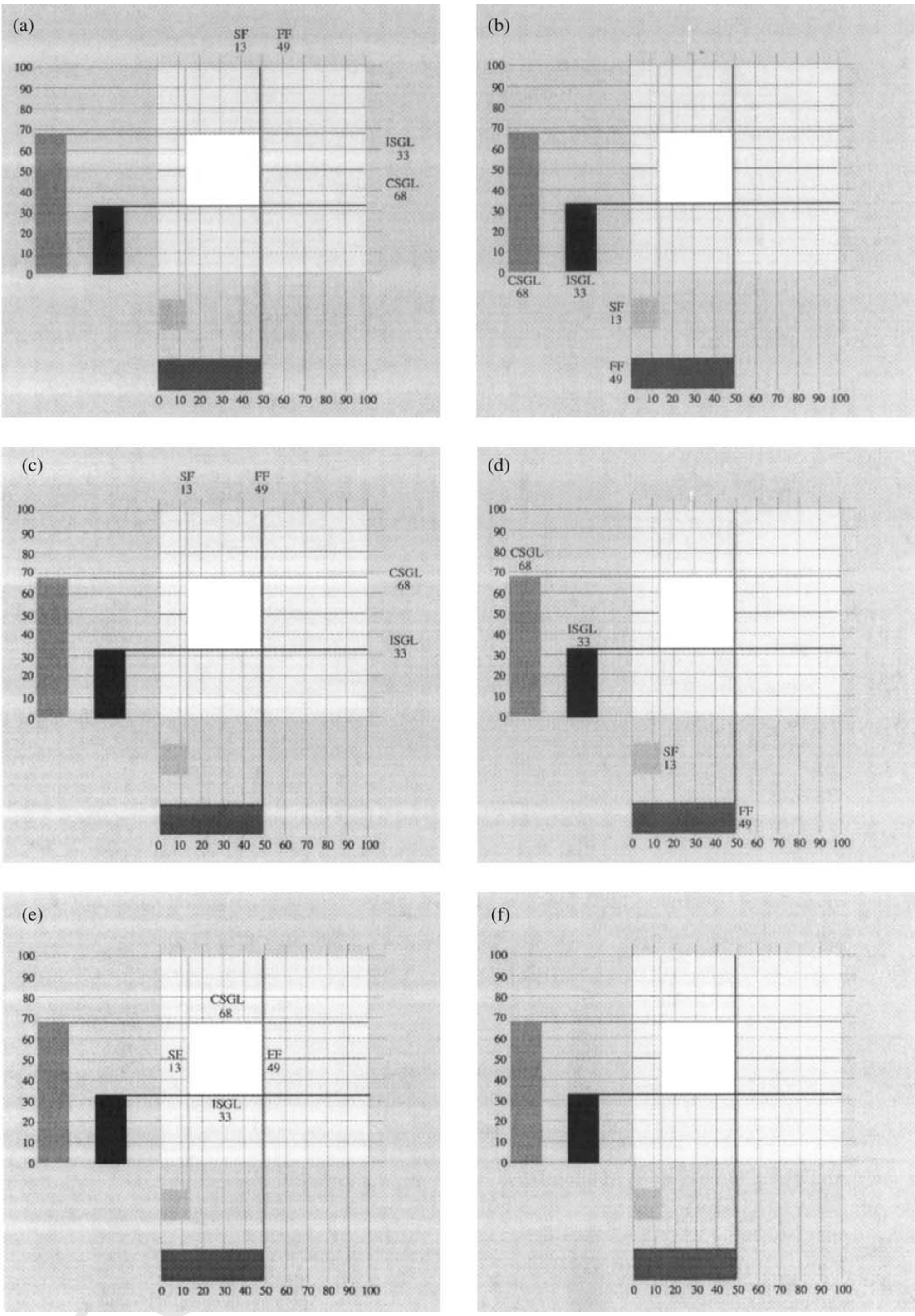

Fig. 1. The six displays evaluated in the study. (a) The static axis display. (b) The static bar display. (c) The dynamic axis display. (d) The dynamic bar display. (e) The digital configural display. (f) The analog configural display.

The second context involves a different category of task demands associated with the use of digital values. An individual will not always know which variable is of interest before a configural display is attended to; the act of considering the data relationships in a configural display might, in fact, alert the individual to the fact that the current value of a variable is interesting or important. The example provided by Hansen (i.e. the need for the precision of digital values during a small leak [9]) is representative. Both the presence of the leak and the precise adjustment required to compensate for the leak (i.e. the quantitative value for a variable) is dependent upon the consideration of existing data relationships.

To simulate the use of digital values to meet this category of task demands a 'criterion' task condition was also included in the evaluation. Rather than a variable name, the experimental prompt in this task described one of the four possible rank-orders between variables (i.e. highest, second highest, lowest, or second lowest). This criterion defined the variable of interest for that particular trial. The user's task was to determine which of the four variables met that criterion and to report its quantitative value. Thus, the exact variable was not known prior to accessing and attending to the display; it became apparent only after the existing data relationships had been considered.

1.5. Predictions

It was predicted that the presence of digital values would improve performance relative to a graphical format that did not have digital values, consistent with previous experimental outcomes [3]. The potential interaction between the placement of digital values (static vs. dynamic) and the nature of the task to be performed (name vs. criterion) was of particular interest. The results of a pilot study indicated that a dedicated spatial position for a digital value (i.e. static placement) produced better performance than a dynamic placement when the variable of interest was known before attending to the display (i.e. name task). It was predicted that this pattern of results would be obtained. In contrast, a dynamic spatial link between the analog graphical components and the digital value of a variable (i.e. dynamic placement) might prove beneficial when the variable of interest could only be determined after explicit consideration of the display (i.e. criterion task).

2. Method

2.1. Participants

The participants were 12 men from an undergraduate ergonomics class at North Carolina State University who received extra credit or $45. All participants had normal or normal-corrected vision and no self-reported color-blindness deficiencies.

2.2. Apparatus

A mobile PC (CTX EzBook 586-150) and a 43.20 cm external monitor (EMC Multisystems, Model SA-770) with 0.28 dot pitch resolution were used to generate and present experimental stimuli. Participants entered responses using the numeric keypad of a standard external keyboard.

2.3. Simulation data

The data used in the experiment were generated in a previous experiment [3] involving a simulated process control application with four variables. Fifty-four system states (i.e. the value of the four variables at a particular point in time) were randomly chosen with the constraint that the difference between each of the variables was greater than 5% units and that the value of all variables was greater than nine. Each value was then randomly assigned to one of the four variables for use in the present experiment.

2.4. Stimuli

Six different displays were evaluated (Fig. 1); the common features will be described. The main window measured 32 cm × 24 cm and was dark gray. The display grid was 10 cm square, light gray, contained *X*- and *Y*-axes (0–100% in 10% intervals), and black grid lines. Trip set points were located at 20 and 80% (horizontal red lines). Each variable was represented as a bar graph to the left (compensated and indicated level) or below (steam and feed flow) the grid (Fig. 1(a)–(f)). Each bar was 1 cm wide with a maximum height of 10 cm and was assigned one of four colors (green, blue, purple, and yellow). Extender lines connected each bar graph with the opposite side of the display grid. The area intersected by these four extender lines formed a rectangle (off-white); the shape, size, and location of this rectangle was an emergent feature determined by the value of the four variables.

The six displays that were evaluated differed only in the presence, location, or behavior of the digital values and are shown in Fig. 1. Five displays contained digital values (Fig. 1(a)–(e)); one did not (Fig. 1(f)—analog configural). Two of these displays (Fig. 1(a) and (b)—static axis and static bar) contained digital values with spatial locations that did not change. Two of these displays (Fig. 1(c) and (d)—dynamic axis and dynamic bar) contained digital values with spatial locations that changed along one axis. One display (Fig. 1(e)—digital configural) contained digital values with spatial locations that changed along two axes.

2.5. Procedure

The subjects were tested individually in an enclosed room. One practice and five experimental sessions were completed (approximately 40 min each). Prior to the practice session the participants were provided with a verbal explanation of the tasks and descriptions/demonstrations of the displays. Participants were instructed to respond as accurately and as quickly as possible. Each session contained six blocks of trials, one block for each of the six displays (random presentation order). A total of 72 trials (random presentation order) were completed during a block of trials (a factorial combination of the two tasks, the four variables/criteria, and nine repetitions of these two factors).

Each trial began with a blank screen. Participants initiated a trial by pressing a key, causing the display and an experimental prompt appeared on the screen. In the name task, participants were provided with the name of the variable whose value was to be reported (steam flow, feed flow, indicated level, or compensated level). In the criterion task the participants were provided with a criterion corresponding to one of the four rank-orders between variables (highest value, second highest value, lowest value, or second lowest value). Participants reported the value of the variable meeting this criterion by typing in a value and pressing the 'enter' key. The screen was cleared at the end of a trial; no feedback was provided. If the participant provided an inappropriate response (e.g. an alphabetic character, or a number greater than 100) the trial was re-administered at the end of the session.

3. Results

Accuracy (error magnitude) was measured by computing the absolute value of the difference between the participant's estimate of a variable and the actual value. Response latency was measured from the appearance of the prompt until the first digit of the participant's response (1/100 s accuracy). Outliers were identified using the test described in Lovie [24, pp. 55–56]: $T_1 = (x_{(n)} - \bar{x})/s$, 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. A total of 950 latency scores (512 criterion and 438 name; 3.95 and 3.38%, respectively) and 314 accuracy scores (248 criterion and 66 name; 1.91 and 0.51%, respectively) were identified as outliers. Non-parametric tests (Friedman ANOVA) were conducted to determine if the outlier distribution was random across display conditions; none of these tests were significant.

Responses were averaged across repetition, variables (or criteria) and session. A set of five pre-planned comparisons was performed for each dependent variable and task. Table 1(a) provides a numeric label for each contrast (left column), a verbal description of the contrast (middle column), and the displays with the associated contrast weights (right columns). The results are listed in the left side of Table 1(b). The accuracy and latency means for each display and task combination are shown in Figs. 2 and 3.

4. Discussion

The results obtained with the five displays containing digital values will be considered first. There was a clear trade-off between the placement of digital values (static vs. dynamic) and the type of task to be performed (name vs. criterion). The dynamic placement of digital values (dynamic axis and dynamic bar, Fig. 1(c) and (d)) resulted in significantly faster and significantly more accurate responses than the static placement of digital values (static axis and static bar displays, Fig. 1(a) and (b)) when a criterion search was required (Table 1(b), Contrast 1c). The exact opposite pattern of results was obtained when a name search was required: the static placement of digital values resulted in significantly lower response latencies than the dynamic placement of digital values (Table 1(b), Contrast 1n). Response latencies have been averaged across the two dynamic and across the two static displays in Fig. 4 to illustrate the pattern of results more explicitly.

The digital configural display (Fig. 1(e)) also incorporated a dynamic placement of digital values; the pattern of results relative to static placement remained essentially the same. The 2c and 2n contrasts did not address this pattern directly, since performance with the digital configural display was compared to all other displays with digital values (Table 1(a)). Therefore an additional set of contrasts was performed to narrow the scope of comparisons to include only static placements (static axis and static bar displays). The results indicate that the digital configural display produced significantly better performance than static placement for the criterion task, $F(1, 11) = 7.75$, $p < .02$, but significantly worse performance for the name task, $F(1, 11) = 33.60$, $p < .0002$ (Fig. 4).

4.1. Interpretation of experimental findings

The interpretation of these results requires an explicit consideration of the activities that were necessary to complete a response. The overall response is separated into four general phases of activity. The participant first needed to identify which of the four variables was to be reported. The participant then needed to search for the relevant visual information that corresponded to that variable and its value. Next, the participant was required to form an estimate of the quantitative value of the variable to be reported. Finally, the participant needed to respond by typing in the quantitative value. These four phases of activity will be referred to as the identification, search, estimation, and response phases.

4.1.1. Name task

The results obtained with the name task will be interpreted first. The identification, estimation, and response phases were similar for all displays. On the other hand, the search phase was quite different for the static and dynamic displays. Two factors are likely to have contributed to the improved performance with the static displays (i.e. static axis and static bar). First, the variable to be located was specified in the experimental prompt. Second, the digital value corresponding to that variable was located in a dedicated spatial location. Thus, there was very little uncertainty during the search phase: the participant knew the exact location of the digital value to be reported.

This is not the case for the displays with dynamic placements (i.e. dynamic axis, dynamic bar, and digital configural displays). Participants possessed only approximate knowledge of the physical location that contained the digital value for a particular variable, because that value could appear in a range of spatial locations. As a result they

Table 1
Displays, contrasts, results

(a) Display and contrasts

Contrast #	Verbal description	Task	Static axis	Static bar	Dynamic axis	Dynamic bar	Digital configural	Analog configural
1c	Static vs. dynamic	Criterion	1	1	−1	−1	0	0
1n	Static vs. dynamic	Name	1	1	−1	−1	0	0
2c	Digital configural vs. other digital	Criterion	1	1	1	1	−4	0
2n	Digital configural vs. other digital	Name	1	1	1	1	−4	0
3c	Axis vs. Bar	Criterion	1	−1	1	−1	0	0
3n	Axis vs. Bar	Name	1	−1	1	−1	0	0
4c	Static-dynamic and axis-bar interaction	Criterion	1	−1	−1	1	0	0
4n	Static-dynamic and axis-bar interaction	Name	1	−1	−1	1	0	0
5c	Digital vs. Analog c onfigural	Criterion	1	1	1	1	1	−5
5n	Digital vs. Analog configural	Name	1	1	1	1	1	−5

(b) Results

#	Latency		Accuracy		Task	Verbal description of results
1c	$F = 6.36$	$p < 0.03$	$F = 12.25$	$p < 0.005$	Criterion	Dynamic significantly better than static
1n	$F = 10.59$	$p < 0.008$		ns	Name	Static significantly better than dynamic
2c	$F = 4.56$	0.06		ns	Criterion	Digital configural better than all other digital displays
2n	$F = 25.22$	$p < 0.0004$		ns	Name	All other digital significantly better than digital configural
3c		ns		ns		
3n	$F = 41.31$	$p < 0.00005$		ns	Name	Axis significantly better than bar
4c		ns		ns		
4n		ns		ns		
5c	$F = 32.81$	$p < 0.0001$	$F = 127.47$	0.000001	Criterion	Digital significantly better than analog
5n	$F = 52.76$	$p < 0.00002$	$F = 123.75$	0.000001	Name	Digital significantly better than analog

were required to search that range to locate the appropriate digital value. In summary, dynamic placement increased response latencies significantly (relative to static placement) during a name search by increasing the uncertainty with regard to the spatial location of the digital value that was associated with the variable specified in the experimental prompt.

4.1.2. Criterion task

The results obtained for the criterion task were substantially different. It is clear that the criterion task was considerably more difficult to complete than the name task, as reflected in the overall increase in response latencies (compare Fig. 4(a) and (b)). The additional task requirements occurring during the initial identification phase are responsible. In particular, participants were required to identify the variable that met the criterion of the search (e.g. the variable with the second lowest value), as opposed to simply reading the name of the variable to be located.

It is also clear that the pattern of results obtained for the placement of digital values was reversed for the criterion task: the dynamic placement of digital values resulted in significantly lower response latencies than static placements (Fig. 4). The interpretation of these results rests upon two observations. First, the emergent features produced by the configural display provided visual information that assisted in the determination of the variable that met the criterion of

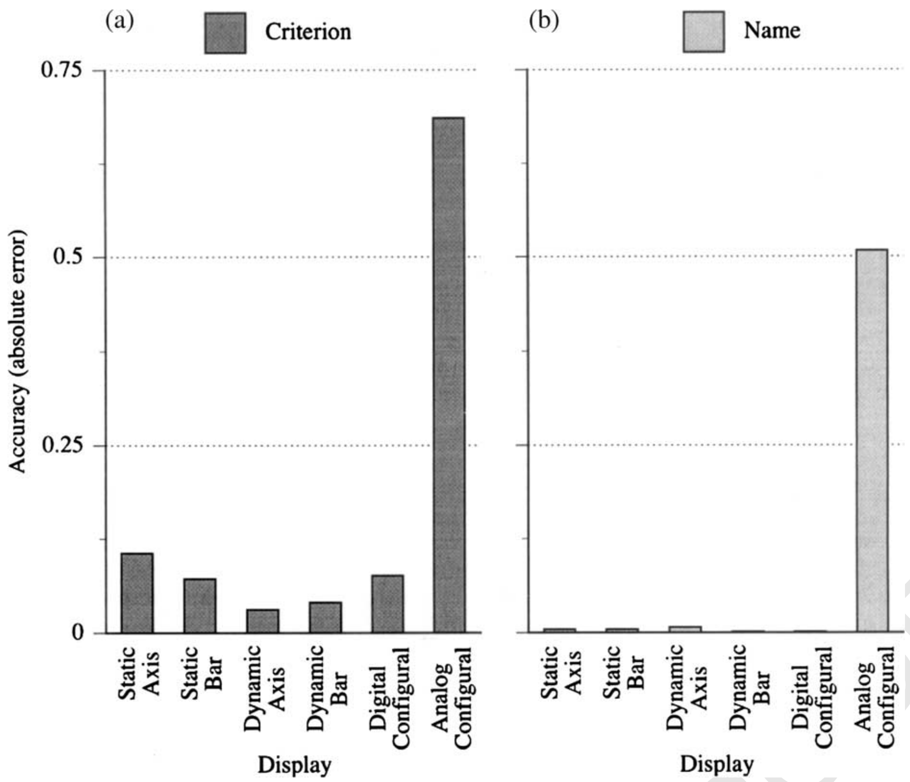

Fig. 2. Mean accuracy (absolute difference) for each display. (a) Criterion task. (b) Name task.

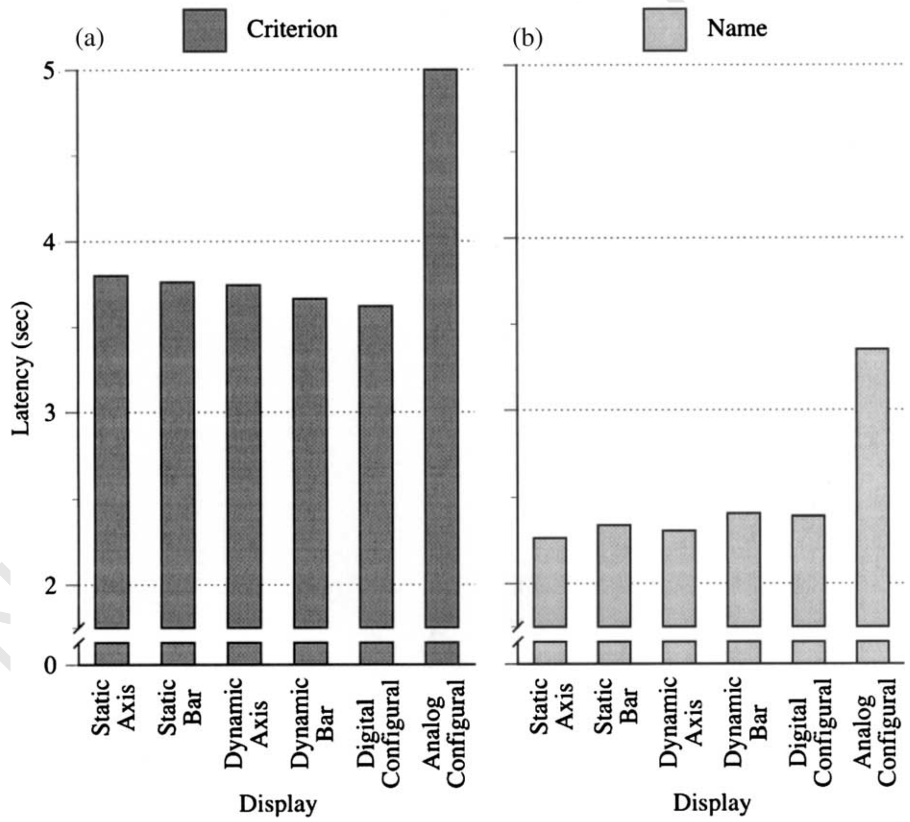

Fig. 3. Mean response latencies (sec) for each display. (a) Criterion task. (b) Name task.

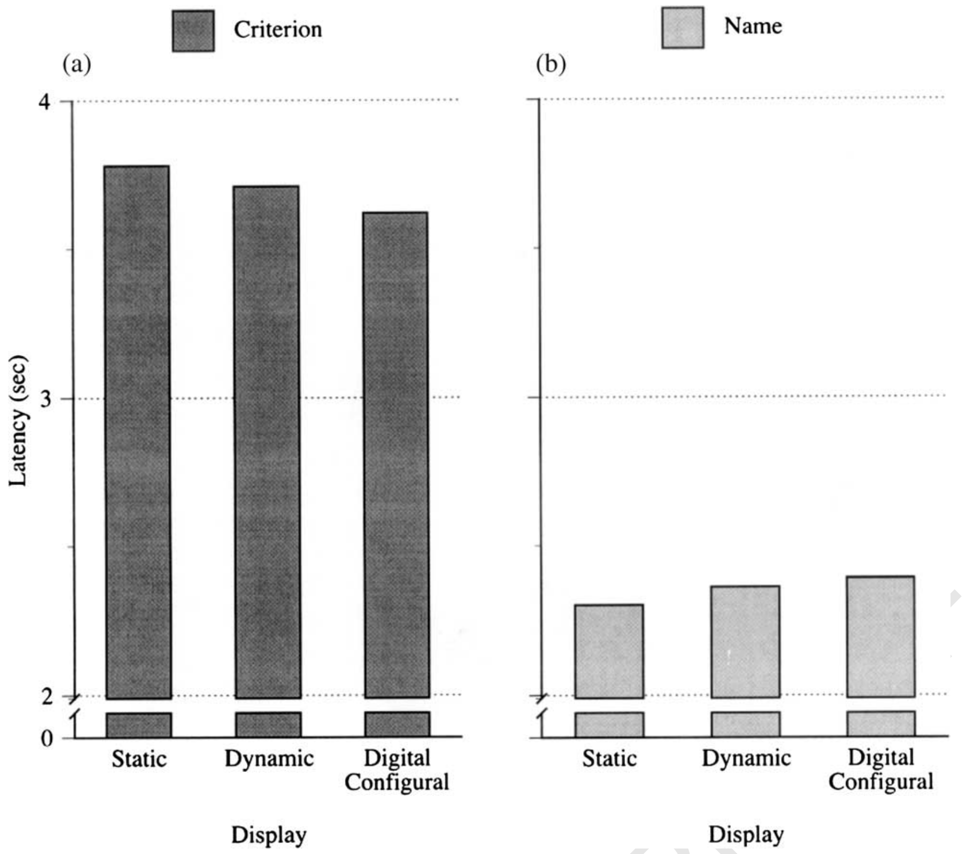

Fig. 4. Mean response latencies (sec) for all displays with digital values. Scores were averaged across similar displays to illustrate findings for dynamic and static placements. (a) Criterion task. (b) Name task.

the search. Second, the configural display provided visual links that served as cues to guide the participants to the spatial location of the corresponding digital value. The details of this interpretation will be described more thoroughly.

4.1.2.1. Identification phase. The first part of the interpretation involves a consideration of how visual features produced by the analog configural display facilitated the identification phase. Two pairs of variables (feed and steam flow; indicated and compensated level) were plotted on each of the two axes. The intersection of these four variables formed a rectangular shape that comprised the configural display. This mapping provided direct visual evidence that specified the larger and the smaller of the two variables that were plotted on the same axis. For example, the variable associated with the right-most side of the rectangle was the largest value for either steam flow or feed flow.

Although it is less obvious, particular configurations and the spatial location of the rectangle within the display grid also provide visual features that specify relationships between variables that are not plotted on the same axis. Fig. 5 will be used to illustrate these points; a diagonal line connecting the lower left corner of the display grid (the origin) to the upper right corner of the display grid has been added to facilitate discussion. First consider an instance where the rectangle was located entirely above the diagonal line in the upper left portion of the display grid (Fig. 5(a)). Under these circumstances the variables with the largest (the top of the rectangle) and second largest (the bottom of the rectangle) values would be those located on the *Y*-axis; the variables with the smallest and second smallest values would be those located on the *X*-axis (left and right sides of the rectangle, respectively). A rectangle located entirely in the lower right portion of the display grid would specify similar relationships, except that the larger–smaller distinction between pairs of variables would be reversed (Fig. 5(b)).

It is also true that the same type of visual information can specify relationships between variables when the two largest and the two smallest values are not located on the same axis. This situation exists when a portion of the configural format falls on the diagonal line (Fig. 5(c)). Under these circumstances the spatial position of the upper right corner and the lower left corner of the rectangle specifies the relationships between variables.

Specifically, the spatial location of the upper right corner of the rectangle specifies the two variables with the largest and second-largest values. In Fig. 5(c) the upper-right corner of the rectangle is above the diagonal line.

This specifies the fact that the largest value is located on the *Y*-axis (i.e. compensated level) and the second largest value is located on the *X*-axis (i.e. feed flow). Similarly, the spatial location of the lower-left corner of the rectangle specifies the variables with the smallest and second-smallest values. In Fig. 5(c) the lower-left corner of the rectangle is above the diagonal line. This specifies the fact that the smallest value is located on the *X*-axis (i.e. steam flow) and the second-smallest value is located on the *Y*-axis (i.e. indicated level).

4.1.2.2. Search phase. In summary, the analog configural display provided visual information that facilitated the identification of the variable that met the criterion specified by the experimental prompt of the criterion task. It is important to note that this analysis alone does not explain the pattern of results that were obtained: all of these visual features were present in all the displays that were evaluated. It is in the next phase of activity, the search phase, that the differences between static and dynamic placement is likely to have had an impact on performance.

The dynamic, static, and digital configural displays varied with regard to the quality of the mapping between a variable in the analog configural display and the location of the associated digital value. The digital configural display (Fig. 1(e)) provided the most direct mapping: the individual digital values were linked directly to the corresponding graphical element (i.e. the appropriate side of the rectangle) in the graphical display. The dynamic axis and bar displays (Fig. 1(c) and (d)) provided mappings that were also direct: the lines emanating from the configural display to the axes provided visual pointers that specified the location of the corresponding digital value. In contrast, the static axis and bar displays (Fig. 1(a) and (b)) provided a mapping that was fairly indirect. For example, in the static axis display (Fig. 1(a)) the only spatial relationships between the analog configural form and the spatial location of the value that needed to be reported were 'above' or 'to the right.'

The results obtained for the criterion task are consistent with the quality of this mapping: the dynamic placement of digital values (digital configural, dynamic bar, and dynamic axis displays) produced significantly lower response latencies than the static placement of digital values (static axis and static bar displays). The dynamic displays provided a direct spatial link between the visual features that specified the appropriate variable and the location of the corresponding digital value. These visual features served as cues that pointed to the spatial location of the appropriate value, reduced uncertainty during the search phase, and therefore decreased the latency of response times significantly. In contrast, the static displays provided a mapping between visual features and digital values that was indirect, and provided only vague information regarding the spatial location of the appropriate digital value.

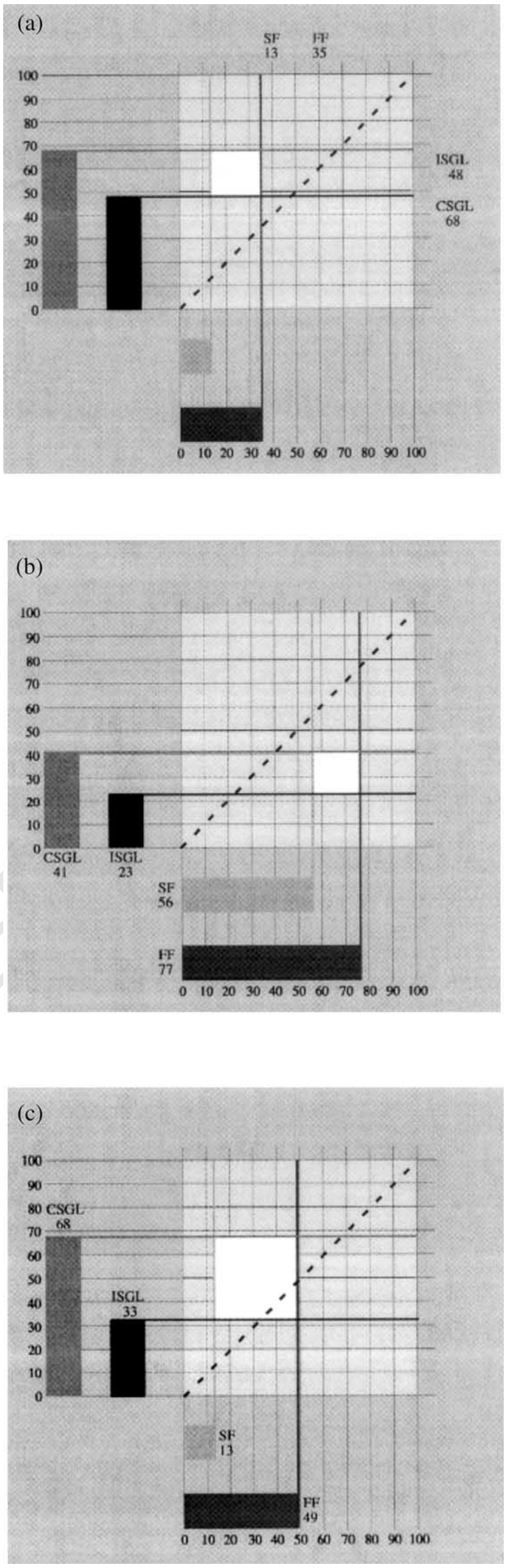

Fig. 5. Graphic illustration of the how the emergent features in the configural display facilitated the identification of relationships between variables. See text for additional details.

4.1.3. Analog configural vs. digital values

One final set of results will be discussed briefly. The display without digital values (the analog configural display, Fig. 1(f)) produced significantly longer response latencies and significantly lower accuracy at both the name and the criterion tasks (Contrasts 5c and 5n, Figs. 2 and 3) than the five displays that contained digital values (Fig. 1(a)–(e)). The interpretation of these results is straight-forward and involves the third phase of activity: estimation. The analog configural display did not incorporate digital values. Therefore, participants were required to perform visual comparisons (between data markers and scale markers) and mental computations (estimates of numerical values to add to or subtract from the numbers associated with scale markers) to estimate the value of a variable to report. These activities were not required for the five displays with digital values: the exact value was clearly specified. The requirement to perform these activities with the analog configural display produced significantly longer response latencies and significantly lower accuracy.

5. General discussion

In the broadest sense, the findings of the present study are consistent with a body of literature that underscores the potential for configural displays to provide effective decision support in complex, dynamic domains. Configural displays can improve performance at tasks that require the consideration of relationships between variables, properties, goals or constraints when they are designed properly [4,21]. On the other hand, the utility of these displays for the completion of tasks that require the consideration of individual variables has been questioned [25]. The present study provides additional evidence that the annotation of configural displays with digital values can be used to overcome this potential limitation. Combining these two general formats produces a single display that is more versatile and more effective than either format alone [3].

A more specific goal was to investigate issues in design that are relevant to the annotation of configural displays with digital values. The present study extends previous research in several ways. First, alternative placements of digital values were evaluated simultaneously under similar experimental conditions. Some of these placements are commonly encountered design solutions (e.g. scientific graphing software often has the convention used in the dynamic bar display, Fig. 1(d), as an option) while some are exploratory solutions (e.g. dynamic links to the configural format [9]). Second, performance with these placements was examined under alternative contexts that were designed to simulate different sets of circumstances and demands that might characterize the use of digital values (i.e. name vs. criterion tasks).

5.1. Trade-offs

The results reveal a reasonably well-defined trade-off between categories of placement (i.e. dynamic and static) and categories of task (i.e. name and criterion). The static placement of digital values facilitated performance when the participant was required to provide an exact numerical value for a variable whose identity was known prior to accessing the display. Under these circumstances a dedicated spatial location for each digital value reduced uncertainty with regard to the location of relevant visual information. Conversely, the dynamic placement of digital values improved performance when the identity of the variable to be reported was dependent upon a criterion of relationships between variables. Under these circumstances the close spatial relationship between visual features in the configural format and the appropriate digital value reduced uncertainty with regard to the location of relevant visual information.

One goal of the present study was to determine if there was an 'elegant' solution to the annotation of configural displays with digital values. An elegant solution would have revealed a single placement of digital values that either simultaneously supported satisfactory performance at both categories of tasks or supported one category without hindering performance in the second. The results indicate that none of the placements provided an elegant solution. Moreover, the interpretation outlined above suggests that interaction between placement and task is a fundamental limitation that is not likely to be addressed through the exploration of other design alternatives. In summary, it seems clear that annotating a configural display will result in a more versatile and effective display. However, the exact manner in which configural displays should be designed to incorporate this annotation is uncertain.

5.2. Practical considerations

Thus, the choice between dynamic and static placements for the annotation of configural displays must be based upon other considerations. The static placement option has several practical advantages. The primary advantage lies in the relative frequency that the two task categories might be expected to occur. The most common uses of quantitative values include monitoring a critical value, communicating its value to others, completing a checklist, or providing input to software modules. Under these and similar circumstances, the identity of the variable that is needed is likely to be known prior to accessing the display. These practical considerations favor the static placement of variables. In addition, placing the digital values in a dedicated spatial position that is consistent across all of the displays that appear in an interface (e.g. across different displays that appear on different pages) is likely to accentuate the performance advantages observed in the present study, which evaluated a single display.

The choice of dynamic placement also has some practical advantages. One such advantage involves the amount of 'display real estate' that is required. Dynamic placement incorporates digital values into the display space occupied by the configural display and does not require additional space, which is not true for the static placement of variables. This strategy requires additional space for each individual variable in addition to the space that is required for the configural display. Hence, the requirement for additional space will become more pronounced with increases in the number of digital values in the configural display. In real world contexts this might represent a prohibitive design limitation.

Dynamic placement has some additional practical advantages that are more subtle, but are potentially far more important. Dynamic placement is likely to provide better support than static placement for less frequent, but perhaps more critical uses of quantitative values. This strategy provides better support for unanticipated, but critical events such as the small leak scenario discussed previously. Furthermore, dynamic placement increases the probability that existing data relationships will be attended to, since the digital variables are embedded in the graphical data relationships portrayed by the configural display. This is not true for static placement: the digital values are located in a dedicated spatial position that lies at some distance from the configural display. Thus, dynamic placement increases the probability that interesting, important, or abnormal system states will be discovered.

5.3. Summary

It should be apparent that the distillation of a set of design principles is not a straight-forward task. The 'first principle' of design that emerges is to incorporate digital values for low-level data into configural displays. The pattern of results indicates that the presence of digital values had a far more profound impact on performance than the alternative placements. However, significant differences were obtained for the alternative placements; they revealed a trade-off and therefore no elegant solution. It appears that any design recommendations for the placement of digital values must be based upon practical considerations. The over-riding practical consideration is the role that the human is expected to assume in today's complex socio-technical systems. Technological advances have placed new demands upon human operators, demands that require them to serve in roles that are primarily supervisory and problem-solving in nature. The dynamic placement of digital values provides better support for these roles, as outlined previously (e.g. increasing the probability of discovering a system abnormality). Therefore, our recommendation is that configural displays should be designed using the dynamic placement strategy that was used in the digital configural display (Fig. 1(e)). In general terms this strategy involves the annotation of a configural form: the digital values for the low-level data should be spatially linked to the corresponding graphical elements in the configural form.

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