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THE DISPLAY OF MULTIVARIATE INFORMATION: THE EFFECTS OF AUTO AND CROSS-CORRELATION, RELIABILITY, AND HETEROGENEITY

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Typically, process control systems involve many variables which can be correlated with one another (cross-correlated), correlated with themselves (autocorrelated), and which are represented by displays possessing varying degrees of reliability. This study examined these factors in an information integration task, which compared the relative advantages of integral and separable displays. The degree of cross-correlation between the cues and the heterogeneity of cue reliability were varied factorially between subjects: the input dynamics and

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20. Abstract (continued)

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THE DISPLAY OF MULTIVARIATE INFORMATION: THE EFFECTS OF AUTO- AND CROSS-CORRELATION, RELIABILITY, AND HETEROGENEITY

BY

PATRICIA M. JONES and Christopher D. Wickens

Abstract

Process control systems typically involve many variables that can be intercorrelated with each other (cross-correlated), correlated with themselves over time (auto-correlated), and that are represented by displays possessing varying degrees of reliability. This study examined these factors in an information integration task which compared the relative advantages of integral and separable displays (pentagons and staggered bargraphs). The degree of cross-correlation between the cues and the heterogeneity of cue reliability (equal or differing values between the cues) was varied factorially between subjects; the input dynamics (auto-correlated or random over time) and display (pentagon or bargraph) were varied factorially within subjects. Results indicated an advantage for cross-correlated information and for the integral display, and also showed a surprisingly strong benefit for the integral display given uncorrelated, randomly-varying information. The results are interpreted within the framework proposed by Wickens and his colleagues of the "display proximity advantage".

Introduction

In a process control environment, it is often necessary to integrate information from various sources in order to make control decisions (Bainbridge, 1974). For example, to evaluate the safety of a nuclear power plant, one should consider variables related to primary coolant inventory, reactor core and secondary heat removal, the control of reactivity, and the quality of the containment facility (Woods, Wise, and Hanes, 1981). Therefore, the experimental task requiring information integration is considered relevant to the study of display formatting in a process control environment. Our goal is to identify variables that may influence the relative superiority of an integrated object display or a separated bargraph display; three such variables are cross-correlation, autocorrelation, and the heterogeneity of display reading reliability. These variables are typically encountered in a real-world process control environment, and as such are relevant and meaningful experimental manipulations. Furthermore, research described elsewhere (Wickens, 1986a; Casey & Wickens, 1986) suggests the likelihood that at least one of these factors -- The correlation between variables -- might be expected to influence the relative effectiveness of separate vs. integrated displays. Before the experiment in which these variables are examined, is described however, we review briefly the potential effects of these four variables that might be expected to influence integration.

Integral and Separable Displays

A useful distinction in display design concerns the integrality of the displayed dimensions. Garner (1970) described integral dimensions as those that produce redundancy gains and interference effects in speeded classification tasks, while separable dimensions exhibit neither of these effects. Typically integral dimensions are perceived "holistically," as a single object, whereas separable dimensions are perceived as separate entities. For example, a rectangle whose width and length represent two variables may be termed an integral stimulus, while the same two variables displayed as separate bars in a bargraph would be called separable.

Lockhead (1966) showed that in judging line lengths and positions, performance was improved with correlated integral dimensions. Garner and his colleagues (Garner, 1969; Garner and Felfoldy, 1970) have used speeded card-sorting tasks to demonstrate that card sorting is faster with redundant, and slower with orthogonal integral dimensions.

Goldsmith and Schvaneveldt (1984) have extended this line of research to multiple-cue probability learning (MCPL) tasks which compared rectangles and triangles (integral displays) to bargraphs (separable displays). Subjects were instructed to learn the relationship between the displays (cues) and some number (the criterion value). Results indicated that integral displays were significantly better for this purpose than separable displays, with both additive and multiplicative relations. Goldsmith and Schvaneveldt concluded that "the integration and use of multiple sources of information can be facilitated by presenting information cues to a judge in a display configuration with integral dimensions" (p. 266).

Similarly, Carswell and Wickens (in press) found that in an information integration task, simulating simple process monitoring, performance was improved with an integral stimulus. This advantage for integral stimuli was labeled the "display proximity advantage" or DPA. The display proximity advantage however was eliminated when task requirements were to treat each channel independently, rather than to integrate their values. Casey and Wickens (1986) failed to find a display proximity advantage for a fault detection task and discovered an advantage instead for separable displays in fault diagnosis. It was argued that since diagnosis in this task (i.e., selecting which variable had failed) involved selective attention to each cue, an integral display would not be expected to show an advantage.

Further investigations by Barnett & Wickens (1986) and Goettl, Kramer, and Wickens (1986), summarized in Wickens (1986), have also demonstrated the effects of task requirements on the relative efficiency of object versus separated displays. These studies have generally shown that the object-display advantage is increased by the degree of integration that a task requires of the displayed attributes, and is attenuated by the degree of focusing or filtering of the attributes that is required.

Autocorrelation

Autocorrelation refers to the extent to which a system's values are correlated with themselves at different points in time. It may therefore be likened to the bandwidth of the variable, characterizing the sluggishness of the system, or the frequency with which continuous events occur. Some studies have examined the effect of input dynamics (i.e., auto-correlated or random over time) on tracking performance, with the general finding that random variation over time is detrimental to performance (Wickens 1986b). However, such tracking tasks are of higher bandwidths than the inputs in the present study, and may not be pertinent here.

Cross-Correlation

A different line of research suggests that information processing is facilitated with cross-correlated information (Wickens, 1984, Moray, 1981). It is hypothesized that the "internal model" of the environment is formed by learning patterns of correlations between cues. This internal model "provides a framework for easier integration of information that is consistent with it and removes much of the burden of working memory associated with processing large amounts of uncorrelated information" (Wickens, 1984, p. 110). In spite of those potential benefits of information correlation, studies of the actual perception of correlation, (as opposed to the use of correlated information in pattern categorization), indicate that people are not very good at perceiving such information. Nisbett and Ross (1980) and Jennings, Amabile, and Ross (1982) examine the distinction between "data-based" and "theory-based" assessments of covariation. Data-based estimates, typically derived from a fourfold "presence/absence" table, are extremely difficult for laypersons to make, even when the data are statistically significant. The major failing in this type of laboratory task is an over reliance on the present/present cell.

Theory-based estimates of covariation are driven by preconceived notions, and are often inappropriately large. Chapman and Chapman (1969) surveyed clinical psychologists and found that diagnoses using the Draw-A-Person (DAP) and Rorshach tests were strongly influenced by the doctors' preconceptions. For instance, patients who exaggerated the eyes in the DAP test were diagnosed as paranoid; this is a widely-held belief that has no basis in actual fact. In general, covariation perception relies too heavily on preconceptions, even in the face of non-supporting data. Of course data do play a role, but not as strongly as they should. The reasons for this persistence are hypothesized to stem from the "representativeness" heuristic (Tversky and Kahneman, 1974) and confirmation bias. An event seen as representative of a certain class of events is then perceived as belonging to that category. Confirmation bias refers to the tendency to seek out supporting evidence - and ignore discrepant evidence - for one's hypothesis. Together, the representativeness heuristic and confirmation bias form the basis for theory-based estimates of covariation. While Moray (1981) has offered a discussion of the potential use of correlation in process monitoring, no specific research on its effects in this environment appears to be available.

Heterogeneity of Reliability

Correlation of information produces a certain "closeness" or proximity of the displayed variables to each other. A second form of proximity is that induced by the object display. Yet a third form relates to the similarity of weighting operations that must be performed on a set of integrated values. If all values receive the same weighting, then integration might be expected to be facilitated by this similarity of cognitive operations. In contrast a heterogeneity of weightings would be expected to impose a greater mental cost on the information processing system (Slovic, Fischhoff & Lichtenstein, 1977). A single mathematical operation could no longer be applied to all variables, and "cognitive economy" would be lost.

Predictioned Interactions

In the experiment to be reported, all of the four independent variables will be factorially crossed. It is possible to some degree, to make some predictions regarding their interactions. In particular, since we expect an overall object proximity advantage given that information is to be integrated, it is of interest to see how this advantage might be modulated by the other three variables. For example, it may be hypothesized that the cost of heterogeneous weighting might be moderated by a heterogeneous (separate object) display; or alternatively phrased, the advantage of the proximate object display will be maximum if the weightings are all also proximate. It may also be hypothesized that this "Compatibility of Proximity" principle applies to the manipulation of cross correlation as well -- a maximum object display advantage with the correlated variables. If an object display is considered to have some affinity with integral dimensions, then this prediction is a derivative of Garner's (1970) observation of an advantage for integral displays for redundant information.

There is however an alternative hypothesis that might be applied to both tne cross and the autocorrelation manipulations. That is that the object display will show its maximum benefit in the most difficult, heterogeneous conditions; in other words, where the burden of task integration is greatest, the object display will help the most. Thus the greatest benefit might be seen in the random, uncorrelated, heterogeneous condition. Outside of

Garner's data, which are only partially applicable because of substantial differences with the present paradigm, few data exist to confirm one hypotheses over the other. However, the results of Casey and Wickens (1986) study, and an interpretation of the relevant literature that those authors and Wickens (1986) have made, are generally equivocal regarding the effect of correlation on object display benefits. The purpose of this experiment then was to examine the potential interactions between these four factors in the context of a multivariate process monitoring task, in which subjects were required to integrate a set of five time-varying readings, to make a single judgment.

Methods

Subjects

Twenty-four university students (twelve males, twelve females) participated in this study and were paid $3.50 per hour for one three-hour session. Six subjects (three males, three females) were assigned to each of four experimental conditions.

Design

The scenario was that of a chemical process plant where the temperature(s) of vats of chemicals were to be monitored. Five temperature readings were represented by either the heights of bars in a staggered bargraph (the separable display) or the distances between the corners and center of a pentagon (the integral display). The subject's task was to estimate the state of the system (the average temperature) from the five cues and indicate the resulting judgment on a 20-point scale ranging from -10 to +10. This scale, along with the displays, was presented on a CRT screen, and subjects' responses were made with a joystick that controlled a cursor along the scale. Each trial lasted 15 seconds; subjects had 10 seconds to look at the display and five seconds to make a judgment. A warning tone sounded 500 msec before the time to respond.

Cross-correlation and reliability were varied factorially between subjects. Subjects were told that the temperature readings were either all from the same vat of chemicals (cross-correlated group) or from five different vats (uncorrelated group). The readings could be of equal (all .5) or differing (.7, .6, .5, .4, .3) reliabilities.

Subjects were given sketches of the displays with the values of reliabilities given next to the appropriate cues. The meaning of reliability was explained to all subjects; they were told that the reliability of a cue indicates its "trustworthiness." A reliability of zero means that the display is useless and gives no information about the true state of the system, while a reliability of one means that the cue perfectly reflects the true state of the system. To those subjects tested with equal reliabilities, it was merely pointed out that the displayed values indicated reliability. The subjects who had different reliabilities were instructed to weight each cue value appropriately to make their response.

System dynamics and display type were varied factorially within subjects. The order of presentation was counterbalanced between subjects to control for practice and fatigue effects. Each subject received 100 trials (five sets of 20 trials) in each of the four conditions.

Subjects were told that there would be two display types (bargraphs and pentagons) and two different kinds of "time lapses" where some sets of trials would be collapsed over several hours and in other sets, each trial would represent a different day of readings. The shorter lag associated with the hourly readings would inject a degree of autocorrelation over the successive trials; while the greater lag between the daily readings was designed to produce random changes from trial to trial. The bargraph and pentagon displays subtended approximately the same visual angle of 5 degrees x 6 degrees. Both displays had been scaled in a previous pilot study to equate the subjective display gain of each. The bargraphs were staggered so that they preserved the same relative spatial relationships between variables as the pentagon (i.e., variable 1 was at the top center, variable 2 was on the far left, variable 3 on the far right, variable 4 on the bottom left, variable 5 on the bottom right). The total design and representations of typical display patterns produce by the two correlation manipulations are shown in Figure 1.

Derivation of the Input Information

Fourteen relatively slowly-changing functions (i.e., with six or seven maxima or minima at most over a span of twenty points) were used for auto-correlated information. For the "random over time" condition, computer-generated random numbers were used. Each sequence consisted of twenty points. These were analyzed to ensure that they were not significantly correlated with each other. For the uncorrelated condition, these five sets were used to drive the cue values. For the correlated case, random noise (randomly adding or subtracting 1 or 2) was added five times to the same master function, and each of the resulting five functions were used to drive the cues. The mean correlation between these functions was +.76.

Results

A performance index was obtained by correlating subjects' judgments with the true criterion values for each block of trials. These correlations were then transformed into Fisher's Z coefficients. An analysis of variance was performed with these coefficients as the dependent measure. Since there were no significant effects involving the reliability manipulation (all p's > .10, although the general trend of superior performance with equal reliability information was manifested in all conditions), data were collapsed over this variable. Figure 2 shows the mean Fisher's Z coefficients for the cross-correlated and the uncorrelated information groups for display types and system dynamics.

Three main effects were prominent: 1) The benefits of highly correlated information ($F(1,23)=122.290$, $p<.001$), 2) The advantage for the integral object display ($F(1,23)=27.394$, $p<.001$), where this display proximity advantage (DPA) is indicated by the upward slopes of the lines in figure 2; and 3) The advantage for random over auto-correlated dynamics ($F(1,23)=7.407$, $p<.05$). As noted above, the manipulation of reliability was not significant and failed to interact with other variables. A significant two-way

		BETWEEN SUBJECTS			
		Cross-Correlated		Uncorrelated	
		Equal Rel.	Different Rel.	Equal Rel.	Different Rel.
Random over time	Integral Display	a		b	
	Separable Display	c		d	
WITHIN SUBJECTS					
Autocorrelated	Integral Display	e		f	
	Separable Display	g		h	

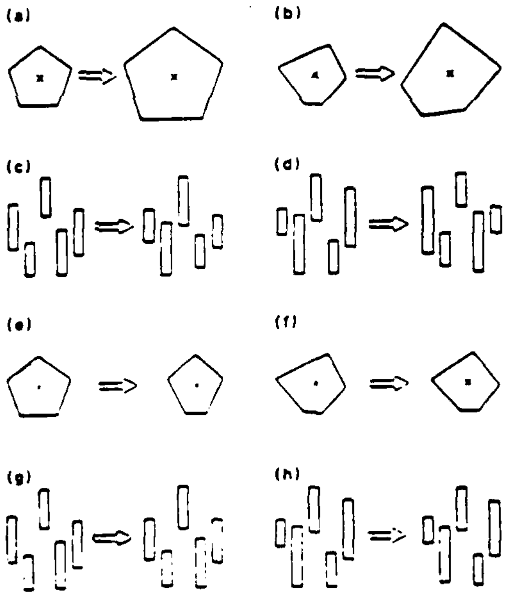

Figure 1. Diagram of the between and within-subject manipulations, with illustrations of the within-subject conditions of the two types of displays and how they might typically change over time given certain dynamics.

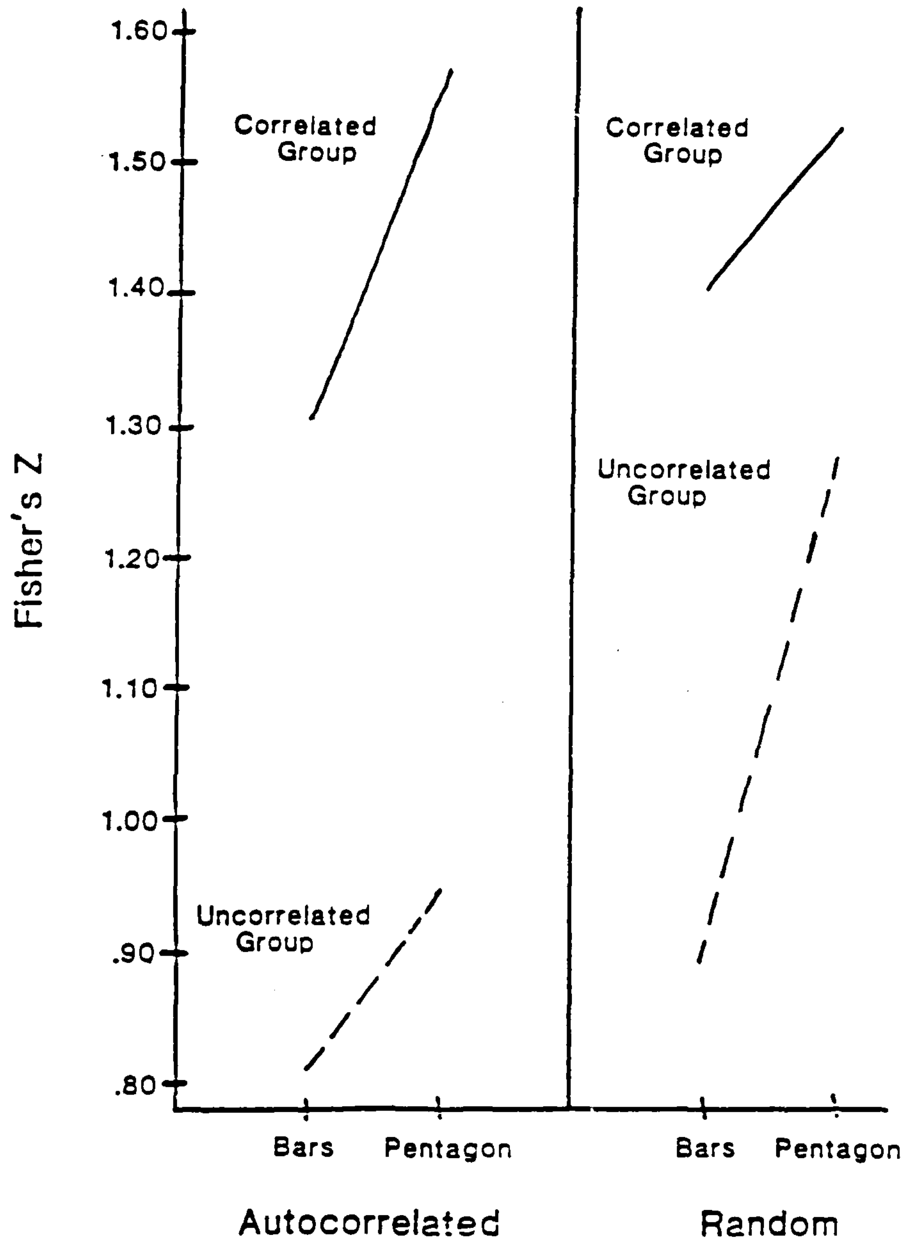

Figure 2. Performance as measured by Fisher's Z coefficients of the correlation between the subjects' responses and the optimal responses as a function of system dynamics and display type (collapsed across the reliability manipulations).

interaction occurred between dynamics and correlation $(F(1,23)=4.807, p<.05)$ such that subjects using uncorrelated information performed significantly better with random dynamics, whereas the autocorrelation manipulation had no effect on subjects in the cross-correlated condition. Finally, a significant three-way interaction between dynamics, correlation, and display $(F(1,23)=5.197, p<.05)$ indicated that performance with uncorrelated, random information was enhanced greatly by the pentagon display, relative to the other three conditions.

Multiple Regression Analysis

A second analysis employed multiple regression--using the subject's response as the criterion and the values of the five cues as predictors--in order to quantify the weighting strategies of the subjects and determine to what extent the subjects with different reliability values actually did weight the cues differently. This approach provides a more fine-grained analysis of performance than the more global correlational analysis. It was expected that the beta weights in the equal reliability case would be approximately the same, unless there were biases associated with certain display positions; while the beta weights in the different reliability condition would reflect the given reliability values such that the obtained beta weights would decline proportionally with cue reliability.

The beta weights were calculated and averaged within each subject for each of the four display/dynamics conditions, and these four sets of values were averaged across all subjects within the correlation/reliability condition. The resulting average beta weights were compared, using the mixed model ANOVA procedure, with these weights as the dependent variable and cue number (position), cross-correlation, reliability, and display as the independent factors (Note: *Because of the limited core storage for the ANOVA* procedure, it was impossible to use all the independent factors simultaneously in the same ANOVA. A separate analysis showed that the dynamics manipulation was not significant, so further analysis has been collapsed across this condition). The resulting beta weights are shown in Figures 3 and 4.

The ANOVA revealed the following significant trends: 1) A main effect of cue number $(F(4,23)=27.198, p=.000)$ such that Cue 3 was the most heavily weighted; 2) A main effect of cross-correlation $(F(1,23)=75.977, p<.00)$ where uncorrelated information yielded higher beta weights; 3) A main effect of display $(F(1,23)=8.118, p=.007)$ which is rather unclear. It appears that in Figure 4, the bargraph enhances the beta weight for Cue 3, relative to the other cues. There were several significant interactions as well: 4) Cue Number x Reliability $(F(4,23)=19.076, p=.000)$. It appears that Cue 3 is weighted more extremely in the different reliability condition and the weights are somewhat more homogeneous in the equal reliability case. 5) Cue Number x Cross-Correlation $(F(4,23)=3.351, p=.019)$. This interaction reflects the extremely low weight on Cue 4 in the cross-correlated condition. 6) Cue Number x Display $(F(4,23)=6.784, p<.0)$. Figure 4 indicates that Cue 3's weight is more extreme with the bargraph display while Cues 2 and 4 are weighted more highly with the pentagon. 7) Correlation x Display $(F(1,23)=5.10, p=.029)$. This interaction is probably due to the very high beta weight on Cue 3 for the bargraph with uncorrelated information. Finally, a three-way interaction of Cue Number x Reliability x Display (F(4,23)=3.0,

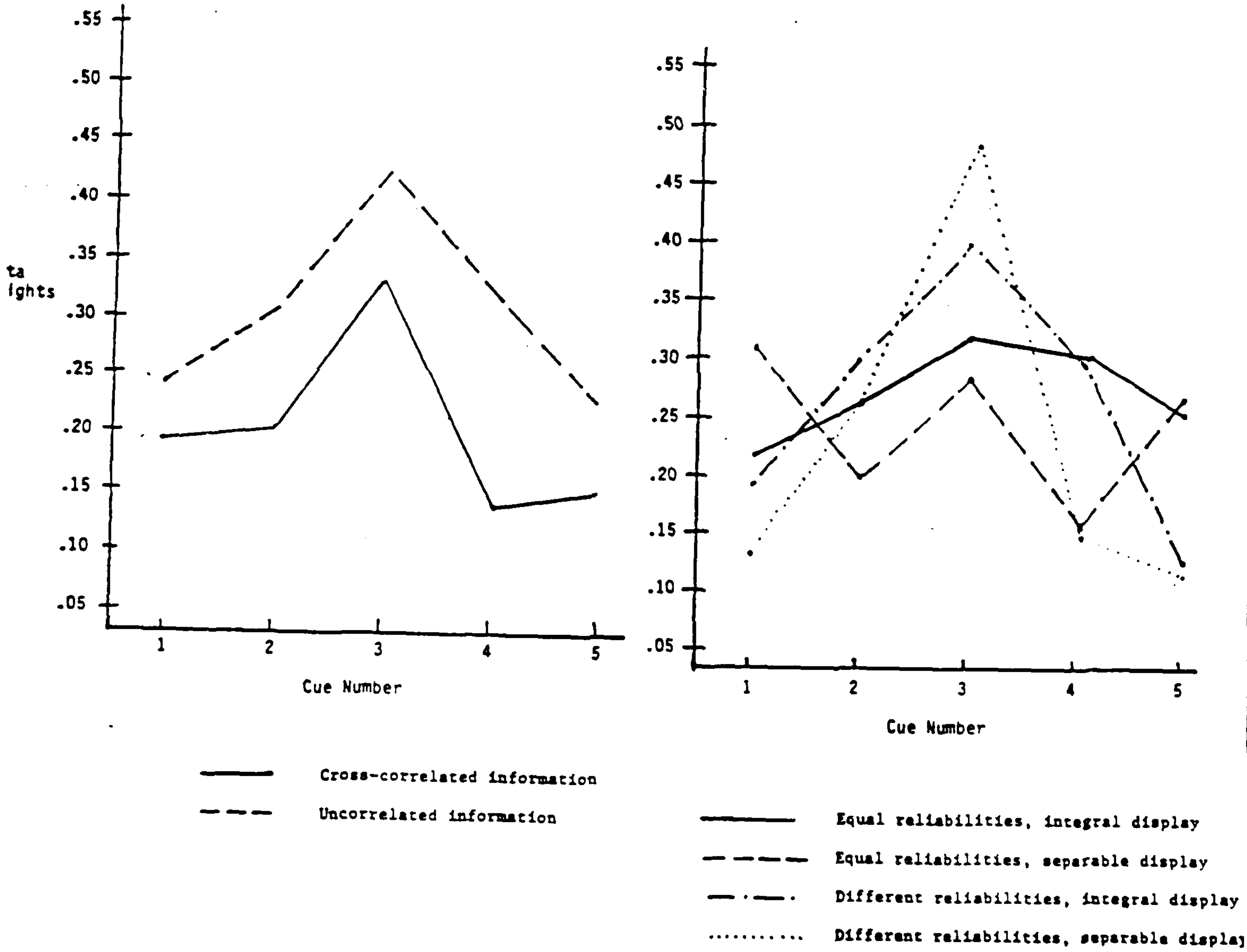

Figure 3. Comparison of the beta weights of the cross-correlated and uncorrelated information groups, collapsed over all other manipulations and plotted as a function of cue number (cue position).

Figure 4. Comparison of the beta weights of the four Reliability x Display groups, collapsed over cross-correlation and dynamics and plotted as a function of cue number.

p=.03) suggests again that Cue 3's surprisingly high weight occurs most prominently in the differentially reliable bargraph condition.

In general, both conditions of reliability exhibit the same basic pattern in which Cue 3 is the most highly weighted. This effect is exaggerated in the different-reliability case and with the separable bargraph display; the weights are somewhat more homogeneous with information of equal reliability and with the integral pentagon display.

Anchoring of Subjects' Responses

Another performance measure of interest was the extent to which subjects tended to "anchor" in this sequential task; that is, the degree to which their responses changed from trial to trial relative to the changes prescribed by the optimal responses. Anchoring occurs when subjects' responses over time do not change as much as they optimally should. The measure used to quantify this concept was the ratio of actual to optimal responses on successive trials:

$$\frac{\text{Actual}(n+1)-\text{Actual}(n)}{\text{Optimal}(n+1)-\text{Optimal}(n)}$$

Optimal performance would yield a ratio of one. Ratios less than one would indicate that the subject is under-adjusting or anchoring; ratios greater than one characterize the zealous over-adjusting subject.

		WITHIN-SUBJECT CONDITIONS			
		AS	AI	RS	RI
	CE	2.31	3.24	0.67	1.57
BETWEEN-SUBJECT GROUPS	UE	5.14	2.79	1.17	2.28
	CD	1.29	2.27	2.43	5.08
	UD	2.84	3.79	1.73	2.20

Table 1. The "anchoring ratio" measure comparing the movement of subjects' responses from trial to trial with the prescribed optimal movement. A ratio of 1 is optimal; of less than one indicates under-adjusting or anchoring; of greater than one indicates over-adjusting. The between-subject groups are CE (cross-correlated information of equal reliabilities), UE (uncorrelated information of different reliabilities). The within-subject conditions are AS (auto-correlated information, separable display), AI (auto-correlated information, integral display), RS (random information, separable display) and RI (random information, integral display).

This ratio was averaged across each within-subject condition, and the values are shown in Table 1. An analysis of variance performed on this measure showed no significant effects. Apparently non-optimal performance was not due to either under- or over-adjusting for changes between trials. While the conditions did not differ from each other, it is noteworthy that most of the ratios are indeed greater than 1.0, thereby; indicating the absence of any conservative anchoring behavior.

Reaction Time Data

Subjects were given five seconds to make their response. Although no instructions regarding the speed of the response were given (except the warning that responses had to be completed in five seconds), reaction time data were collected and analyzed via the analysis of variance. No meaningful trends were found in these data.

Verbal Protocols

Informal verbal protocols reveal that most subjects preferred the integral display, often commenting that it was easier to look at a single shape rather than a collection of bars. The pentagon was apparently perceived holistically; subjects reported that they "looked at the whole shape" rather than attending to the distance between each vertex and the center. Interestingly, this preference appears to be task-dependent, as a comparison of the identical pair of displays made by Casey and Wickens (1986) revealed preference for the bargraphs. The strategies used with the bargraphs were sometimes quite elaborate; several subjects said they compared the tops of the lower bars to the bottoms of the upper bars or used shadows on the screen in an attempt to gauge the absolute heights of the bars.

In general, subjects did not notice a great deal of difference between the random and auto-correlated dynamics. Several commented that the random dynamics were "jumpier" or that the auto-correlated condition was "more stable," but most reports indicated that this manipulation was not particularly potent from a subjective standpoint.

In the differential-reliability condition, most subjects reported trying to concentrate on the three most reliable cues, which comprised the upper half of the display. Some others admitted that they did not take into account the reliabilities and ignored the differential weighting in making their judgments.

Discussion

Display Proximity Advantage. The most prominent finding in the current data was the consistent performance advantage of the integral display (the pentagon) over the separate bargraph display. It has been proposed that this display proximity advantage or DPA might be affected by the degree of correlation of the information and by the amount of information integration necessary to perform the task (Casey and Wickens, 1986). In the present study, the task required complete integration of information (i.e., a many-to-one mapping existed between stimulus and response). This is in contrast to the Casey and Wickens study, which also examined the display proximity advantage but in the context of a fault diagnosis task, where the amount of integration was considerably less (a one-to-one mapping of stimulus to response). The nature of the task (i.e., integrating information versus focusing attention on a particular variable) is a major determinant of the superiority of one display type over another (Kramer et al., 1986; Goettl et al., 1986; Wickens, 1986a; Wickens et al., 1986). Integration tasks are more compatible with integral displays, while tasks involving selective attention or independent processing of several variables are better served by separable displays. This fact accounts for the difference of the findings of the present experiment and the Casey and Wickens study; here a clear advantage for the pentagon display was present, whereas Casey and Wickens found no such advantage. Other studies have supported the present results that integrating information is facilitated with integral displays (Carswell and Wickens, in press; Goldsmith and Schvaneveldt, 1984).

Correlation. In the present study, correlation was explicity manipulated by both cross-correlation and autocorrelation. The expected robust effect of cross-correlation on performance supports the general finding that cross-correlated information is easier to process. Such information is more homogeneous and thus more easily averaged than uncorrelated information (e.g., it is intuitively obvious that to average 6, 6, 6, 5, 6 is easier than to average 6, 9, 11, 5, 2). Note that in the cross-correlated case of this example it is not necessary to look at all five numbers in order to come up with a reasonably close estimate of the average. Moray (1981) observed that during normal operation of a process control system, the operator need only sample one variable from a group of highly intercorrelated variables. It would be interesting to see whether this "correlation advantage" holds for negatively correlated variables or positively correlated yet disparate quantities. Correlation and homogeneity often go hand-in-hand in the real world, but they are independent concepts whose separate effects on performance should be examined in greater detail.

Beyond this main effect of cross-correlation, the interactive effects were such that the DPA was greater with uncorrelated cues. This finding is in keeping with the general framework proposed by Casey and Wickens (1986), although contradictory to Garner's research which indicates the greatest integral display advantage with redundant information. However, when redundant dimensions are employed, the typical Garner paradigm of speeded card-sorting is essentially an integration task. The redundancy of the information gives rise to the integration of the task in that a many-to-one mapping of two or more redundant stimulus dimensions to a single response now occurs. It may be that this integration act rather than the correlation (redundancy) per se is the essential reason for the advantage of integral dimensions with redundant information.

The main effect of autocorrelation was somewhat surprising, in that performance was, if anything, improved in the random condition. It is likely that the delay between subsequent trials was sufficiently great that subjects' memories were unable to use the information offered by the autocorrelation. Each judgment in either condition was made relatively independently of the previous judgment. This finding is supported by the failure to observe any substantial employment of anchoring and adjustment. A more rapid sequencing of inputs or display updates as, for example, is found in tracking, might well bring about an advantage for autocorrelation.

The autocorrelation manipulation did however modulate the DPA; the greatest gains were found with information varying randomly over time. The form of the three way interaction that was obtained indicated that the DPA in general was greatest with the most uncorrelated information--uncorrelated both over time and between cues. Therefore it might be hypothesized that when information is difficult to integrate (e.g., is uncorrelated and varies randomly over time), the DPA is enhanced because it "does more work" for the subject. Since information in an integral display has already been integrated into a single object, the human is required only to evaluate, rather than to integrate and evaluate, information. A second possible influence is that dramatically-varying, irregularly-shaped pentagons characteristic of the uncorrelated conditions are more salient perceptually than bars of different heights. One subject commented that she found such pentagons "more interesting to look at."

Reliability. The third variable hypothesized to affect the DPA was the heterogeneity of reliability. In fact, however this variable did not have any significant effect on performance, although subjects with equal reliability values consistently performed slightly better than subjects who were required to differentially weight information. One possible explanation for this lack of significance is that the chosen reliability values were not very different; with more widely varying reliabilities a more prominent effect may have been manifested (e.g., weighting cues with the values of .9, .7, .5, .3, .1 rather than the sequence of .7, .6, .5, .4, .3 used here). The correlation between the prescribed optimal responses in the equal and differing reliability conditions was very high (mean r=.98), which suggests that differences in performance between these two conditions would also be rather small.

The general trend of slightly more homogeneous beta weights for the equal reliability condition was not surprising, since equally reliable cues should have been weighted approximately the same amount. Also, relatively greater homogeneity of the weights was found with the integral display. The latter result fits in nicely with the idea that selectively attending to cues (in order to weight them by their reliability) is a process that is less compatible with an integral display. If so, then differential weightings may be "evened out" over the features of an integral object display. In fact, one subject in the differential reliability condition stated that he tried to weight information appropriately with the bargraph display, but ignored the weights with the pentagon display.

The most puzzling result is the persistently high weighting on Cue 3. Apparently subjects attended to this cue the most and thus were biased to look at the upper right part of the display. Why this should be so, especially for the different reliability group who should optimally attend the most to the top center cue (Cue 1), is unclear.

Concluding Remarks

The present study has examined some fundamental display issues in process control. While the current paradigm is not a high-fidelity simulation of the real world, it is at least a first step in examining how the dynamic properties and correlational structure of information interact with display format. Such an investigation can indicate the relative advantages of different types of displays, and can contribute to a generic, information processing theory of display design applicable to real-world process control systems. The results of the present study also provide a clear unambiguous data point in the "space" presented in Casey and Wickens (1986) and elaborated in Wickens (1986a). This space attempts to elucidate the stimulus and task conditions that modulate the display proximity advantage.

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