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A Preliminary Investigation Of The Time Tunnels Display Design Technique

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Two forms of decision support were evaluated using a simulated process control task environment. The time tunnel display design concept provides temporal (historical) information about the value of variables and relationships over time using perspective geometry and the depth plane. The compensated level variable is a quickened display that provides estimates of system state that are not confounded by counter-intuitive and time-delayed thermodynamic effects. These two forms of decision support were applied factorially (present, absent) to produce four experimental conditions. The results for system control and fault detection tasks indicate that display quickening improved performance significantly while the time tunnel displays did not. The results for data extraction tasks (reporting the values of system variables) was dependent upon the quality of the mapping between properties in the domain and visual features in the display. Methodological factors that may have influenced the results are considered and subsequent evaluations of the time tunnels design technique using alternative methodologies are discussed. It is concluded that the time tunnels display design concept has potential as a form of decision support and is worthy of additional research efforts.

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INTRODUCTION

Advances in technology provide various forms of computing power that can be used to improve the overall performance of human-machine systems. One design approach that has evolved to harness this power has been referred to as "cognitive systems engineering - CSE" [1]. This approach emphasizes that developing effective interfaces and displays requires a deep understanding of the constraints (e.g., goals, physical, functional) that are inherent to a work domain. The CSE approach provides analytical tools (e.g., abstraction and aggregation hierarchies) for discovering these constraints. These constraints then drive the design of interfaces and displays. The core problem in implementing effective displays is to provide visual representations that accurately reflect this complex and hierarchical structure.

The CSE approach has been applied successfully to a number of domains, but particularly good examples can be found for process control. Process control provides unique challenges for display design: the settings are complex, dynamic, and typically have many-to-many mappings between the goals that are to be achieved and the resources that are available to achieve them. However, many interfaces and displays are not particularly effective in providing decision support. Historically these interfaces were developed using a "single-sensor, single-display" design philosophy: each measured variable was presented in the interface with a unique display (usually an analog meter). This resulted in "opaque" interfaces that placed inordinate demands on the operators, who were required to collect and mentally integrate low-level data to determine higher-level properties and their relationships to system goals.

A number of researchers have discussed alternative approaches to interface and display design [2-8]. Although the terminology and theoretical underpinnings are somewhat different, all these approaches share a common denominator: the goal is to utilize display technology to transform decision-making from a cognitive activity (drawing upon limited-capacity resources such as working memory) to a perceptual activity (drawing upon virtually unlimited perceptual resources such as pattern-recognition). This approach to decision support results in the design of decision aids that capitalize upon, rather than replace, natural human intelligence (contrast with approaches that develop advisory or expert systems).

Configural displays and temporal information

Our research has focussed on issues in the design of "configural" displays, where individual variables are plotted together to produce geometrical forms. Configural displays can be contrasted to "separable" displays, where each variable has a unique graphical representation (e.g., a bar graph display). Configural displays produce "emergent features" which are higher-level visual properties that arise from the interaction of lower-level graphical elements [9]. The key to the design of effective configural displays is an appropriate mapping between the constraints that exist in a domain and the emergent features that are produced by the display [10]. Configural displays can improve overall system performance by collecting and integrating system data into representations that exploit the inherent pattern-recognition capabilities of the human and decrease reliance on limited-capacity resources such as working memory [5].

One critical issue that has received very little attention in the research literature is how configural displays might be designed to convey "temporal" information (i.e., the value of variables and their relationships over time). This type of temporal information should be very useful for any system where overall system dynamics are governed by the laws of nature (e.g., process control). In simple terms, knowledge of past system states should be very useful in determining future system states. As Wang [11] has pointed out, this is a relatively straight-forward expression of the laws of control theory. Temporal information has traditionally been presented in "strip chart" or "trend" displays that provide a historical trace of individual variables but limited emergent features.

One attempt to combine configural displays and temporal information is provided by Hansen

[12] who developed the "time tunnels" display design technique. This technique uses perspective geometry and the "depth plane" to present variations in geometric forms over time. The original implementation of this concept [12] is illustrated in Fig. 1. Two variables (inlet and outlet temperatures) are represented for two system components (reactor and heat exchanger) across ten time intervals. The current values of these variables appear as the outer-most quadrangle (annotated with numerical labels). Each additional quadrangle represents a configuration of the four variables as they appeared at some point in the past. These quadrangles are plotted in the "depth plane" and are scaled according to the laws of perspective geometry; configurations that appeared earlier in time are plotted deeper in the depth plane.

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Insert Figure 1 about here

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Alternative implementation of the time tunnels display concept

The present investigation evaluated an alternative implementation of the time tunnels display design technique using a part-task simulation of a process control task: the manual control of feedwater. This simulation models the basic dynamic characteristics (second-order, non-minimum phase) of a steam generator in a nuclear power plant. Four display conditions were evaluated.

The "baseline" display incorporates the funnel metaphor first introduced by Vicente [13]. It presents three variables that are critical to the manual control of feedwater task (see Fig. 2). The level of coolant in the steam generator ("indicated level") is plotted as a bar graph on the left side of the display. Indicated level is the single most important consideration in the manual control of feedwater task (it determines when automatic shutdowns occur). The "stippled" fill underneath the horizontal line representing indicated level emphasizes the current value of this variable. The rate of mass entering the steam generator ("feed flow") is plotted as a horizontal bar graph at the top of the display. The rate of mass leaving the steam generator ("steam flow") is plotted as a horizontal bar graph at

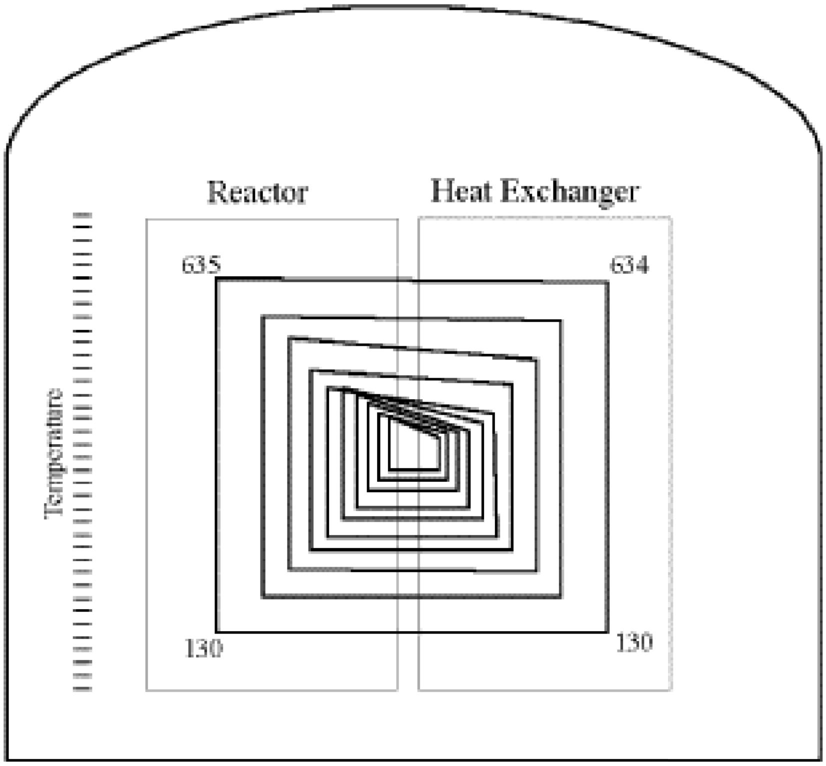

Figure 1. The time tunnel display concept as introduced by Hansen [12]. System states that occurred previously in time are presented in the depth plane as successive distortions of four-sided geometrical forms that are scaled according to the laws of perspective geometry.

the bottom of the display. The relationship between mass in and mass out (mass balance) is represented directly by the line connecting the steam flow and the feed flow bar graphs. The orientation of this line is an emergent feature that specifies mass balance. This mass balance indicator will assume a visual appearance that is similar to a funnel when a positive net inflow exists (i.e., feed flow is greater than steam flow) and indicated level will eventually rise under these circumstances (much like the volume in a container beneath a funnel).

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Insert Figure 2 about here

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A simplified version of this display with the time tunnels design technique applied is illustrated in Fig. 3. Some of the lawful relationships between visual appearance and spatial layout that occur in natural scenes [14] are incorporated into this display. One primary set of considerations is related to the static laws of perspective. Objects that vary with regard to their degree of spatial displacement away from an observer will also vary with regard to the size of the visual angle that is projected on the observer's retina (e.g., an object that is farther away from an observer will project a smaller visual angle than a similar sized object that is closer). Similarly, parallel lines appear to converge in the distance.

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Insert Figure 3 about here

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A "perspective grid" was constructed using the laws of perspective geometry and the following assumptions. A monocular observer is viewing a picture plane (100 cm square) that is located 500 cm away (centered in the observer's field of view); the outline of this picture frame forms the outermost rectangle in the perspective grid (and represents the current time). The additional rectangles represent the outline of the same picture frame as it would appear after successive displacements of

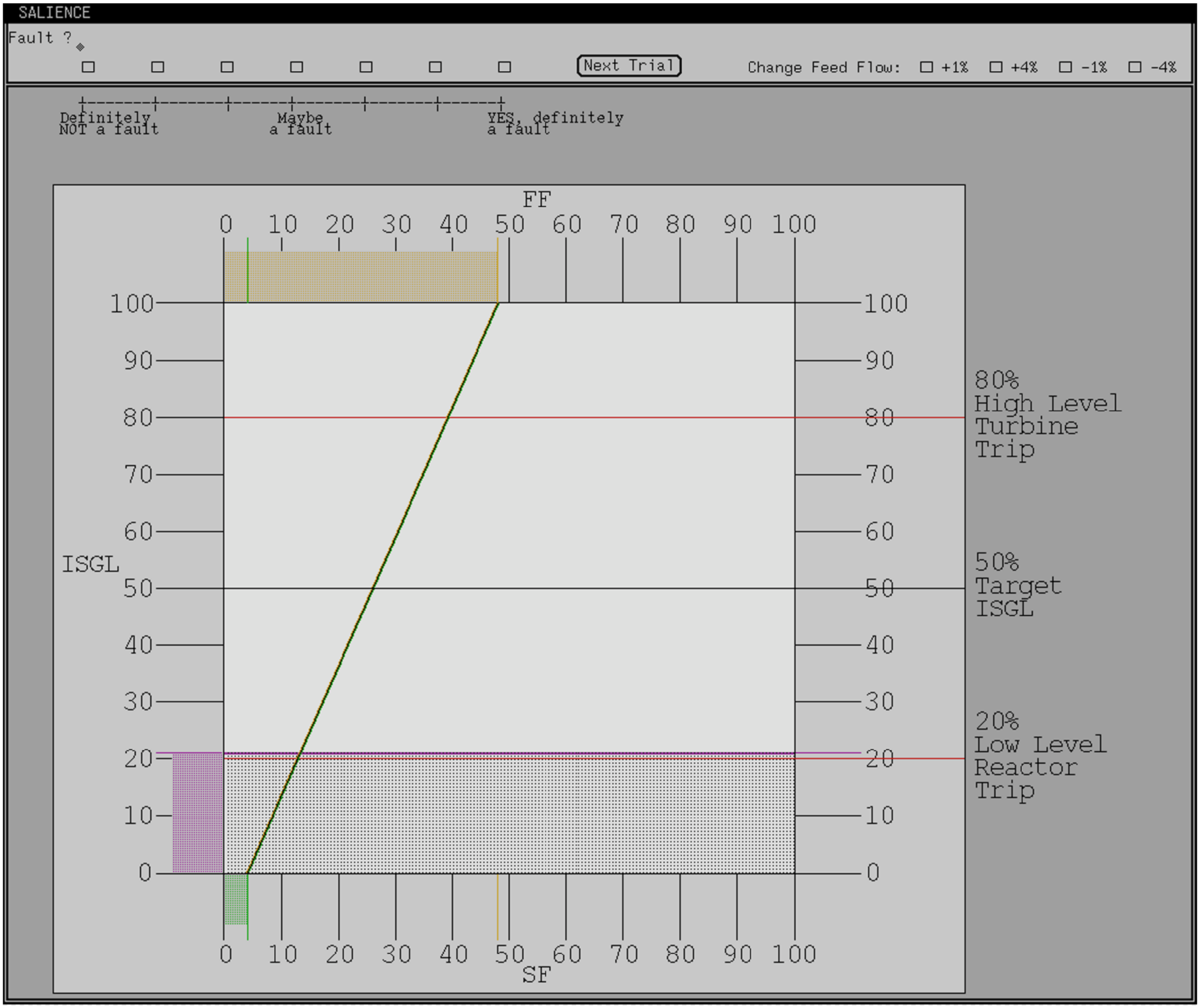

Figure 2. The baseline configural display. This display represents key variables in the manual control of feedwater task which include the indicated level in a steam generator (ISGL), the rate of mass flowing into (feed flow -- FF) and out of (steam flow -- SF) a steam generator, and the property of mass balance (i.e., the difference between steam flow and feed flow).

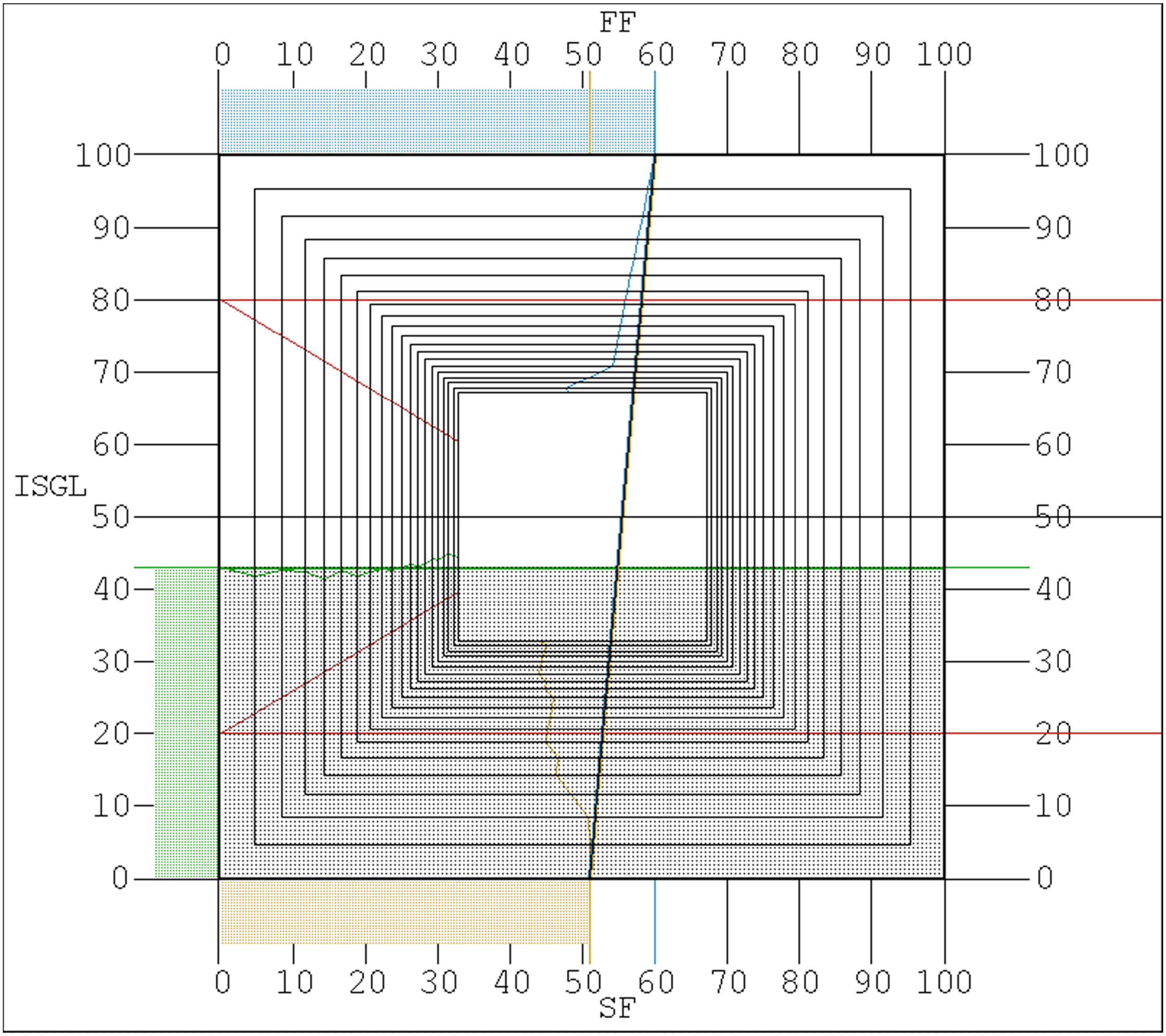

Figure 3. A simplified version of the time tunnel display concept as implemented in the current experiment. A perspective grid is formed using perspective geometry which is then used as a framework to plot system variables across time.

100 cm away from the observer. Each successive rectangle plotted deeper in the depth plane represents a point more distant in time.

Note that the perspective grid was a static framework that was used to present the values of individual variables, goals, and constraints over time. This framework (and the laws of perspective geometry) allows the changes in variables across time to be specified by geometrical cues. Consider the trip set point variables of 80% and 20% as they appear in Fig. 3. There is a "perspective trend" for each of these two variables (the two lines located on the left and the inside of the tunnel). Note that these lines are straight. This is visual information specifying the fact that the value of these set points did not change across time. Also note that the perspective trends converge in the depth plane (much like train tracks in the distance), thus providing visual information specifying that the difference between these two variables remained constant across time. In contrast, consider the perspective trends for steam flow (bottom of the tunnel), feed flow (top of the tunnel) and indicated level (left side of the tunnel). These perspective trends are not straight lines, and the form of each line specifies exactly how the variable has changed.

A second set of lawful relationships that occur in natural visual scenes is related to Gibson’s analysis of ecological optics and the ambient optical array [14]. Objects in the environment are specified by optical borders of contrast or texture, which in turn allows them to be differentiated from other objects and the background. The specification of these borders occurs because the structural composition of these objects (reflective aspects of the faces and facets) causes the ambient light to be reflected differentially.

Several graphical techniques were used to create optical borders in the final version of the time tunnel technique. Fig. 4 illustrates the second display condition (the "tunnel" display). The portion of the perspective grid to the left of the mass balance indicator line is shaded to create a "perspective tunnel." This provides an optical border that highlights a critical domain property (i.e., mass balance). The tunnel metaphor is enhanced by using darker gray-scale shading for rectangles that lie deeper in the depth plane (just as a real tunnel is more dimly lit at its furthest extent). The value of indicated level across time is emphasized through an optical border formed by darker and lighter gray-scale shading corresponding to the portion of the perspective tunnel that lies beneath and above past values of indicated level.

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Insert Figure 4 about here

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A third set of lawful relationships that were incorporated into the time tunnel display involves optical transformations of the visual array that are produced by the motion of objects in the environment. The surfaces of a rigid object will occlude (wipe out at the leading edge) and uncover (make visible at the trailing edge) the surfaces of other objects and the background as it moves in space. Similarly, its surfaces can be wiped out and/or uncovered by the surfaces of other objects. The exact nature of the optical transformation depends upon a number of factors including the observer viewpoint, the environment, and relative spatial position and motion of objects. These optical transformations provide useful information regarding spatial layout. For example, consider an instance where one object in motion occludes and then uncovers a second object in the environment. This transformation is visual evidence specifying that the first object lies closer to the observer in space than the second object.

This type of visual transformation was used in the time tunnel display to specify and accentuate the value of mass balance over time (see Fig. 4). Each set of four points on the right-hand side of the perspective tunnel (i.e., the two feed flow and the two steam flow values associated with two adjacent time frames) were used to form a series of visual planes. Each plane was shaded with the two gray-scale fills that were appropriate for that time frame; these planes were plotted in serial order from most distant in time to most current in time. The end result was that portions of the perspective grid,

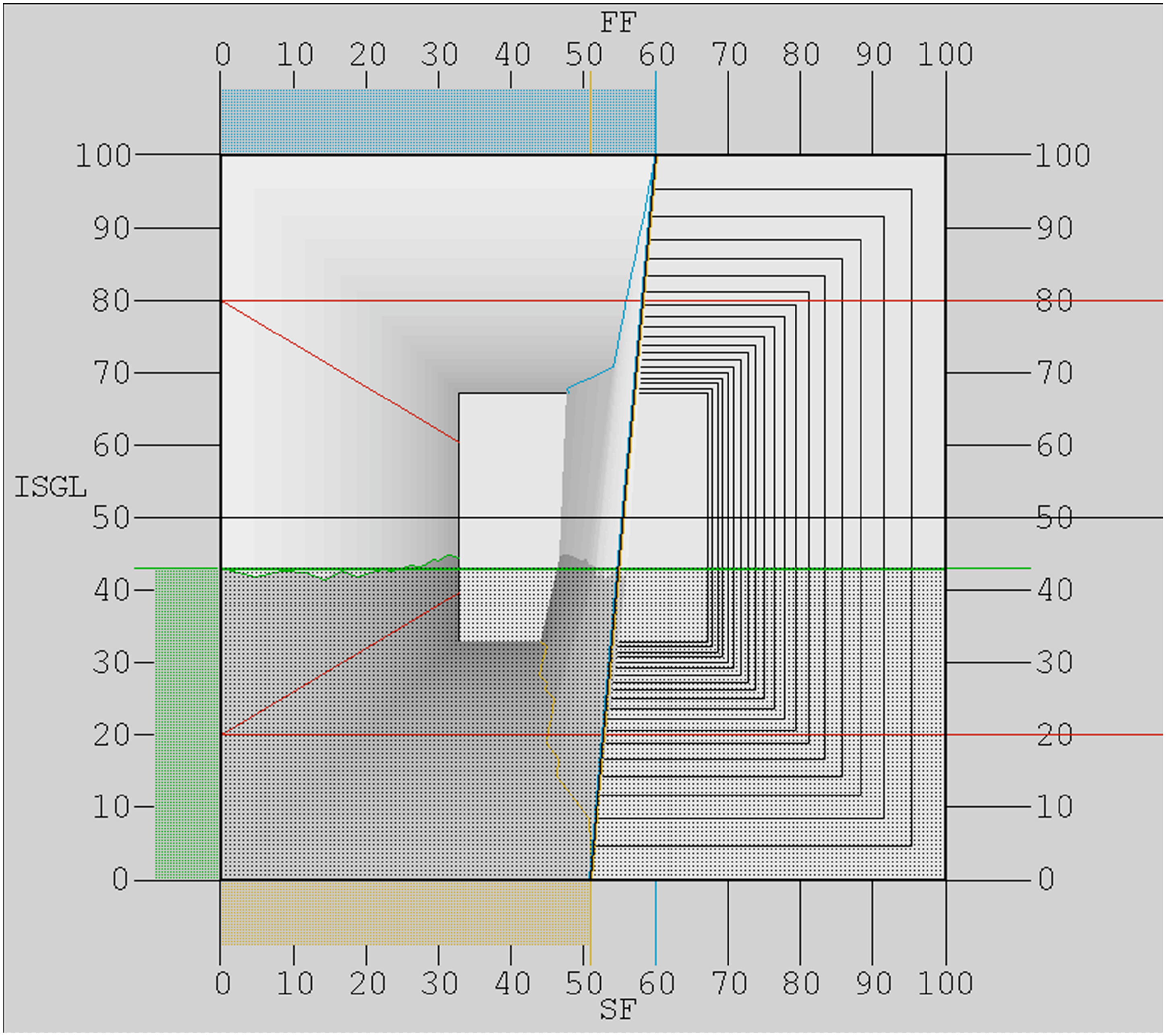

Figure 4. The time tunnel configural display. This display adds gray-scale shading to the perspective grid, thereby emphasizing the tunnel metaphor and critical data relationships (i.e., mass balance over time).

perspective tunnel, and older planes appeared to be occluded (or uncovered) as the screen updated, thereby providing visual transformations (and the resulting optical borders) that specified the relationship between feed flow and steam flow (i.e., mass balance) over time. To aid in visualizing this dynamic behavior one might imagine a flag furling in the wind that is being viewed by an observer from an up-wind position. Vertical portions of the flag would be covered and then uncovered as the air waves worked their way from the front to the back of the flag.

Compensated level: a "quickened" variable

The third display (the "compensated" display) is exactly the same as the baseline display, except for the addition of a calculated variable: compensated steam generator level ("compensated level"). This variable appears as a bar graph on the right axis of the display (Fig. 5). Previous work domain analyses and research [15] have indicated that a primary factor contributing to the difficulty of the manual control of feedwater task is the counter-intuitive and time-delayed effects that are associated with indicated level. Compensated level was developed to provide a mathematical estimate of indicated level that is not confounded by these effects. This variable provides an estimate of what indicated level (i.e., the critical variable to be controlled) will be after any counter-intuitive energy effects and time-lags have dissipated. Thus, compensated level is very similar to a "quickened" display because it reduces the need for an operator to mentally determine derivative information necessary for control. As McCormick [16, p. 221] indicates, "The quickening ... indicates, in effect, what control action to take to achieve a desired system output." The specific approach used in the development of compensated level was sufficiently novel to be awarded a US patent [17].

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Fig. 6 illustrates the fourth display (the "combined" display). This is the same as the tunnel display, except that two visual components have been added: 1) a bar graph and a perspective trend

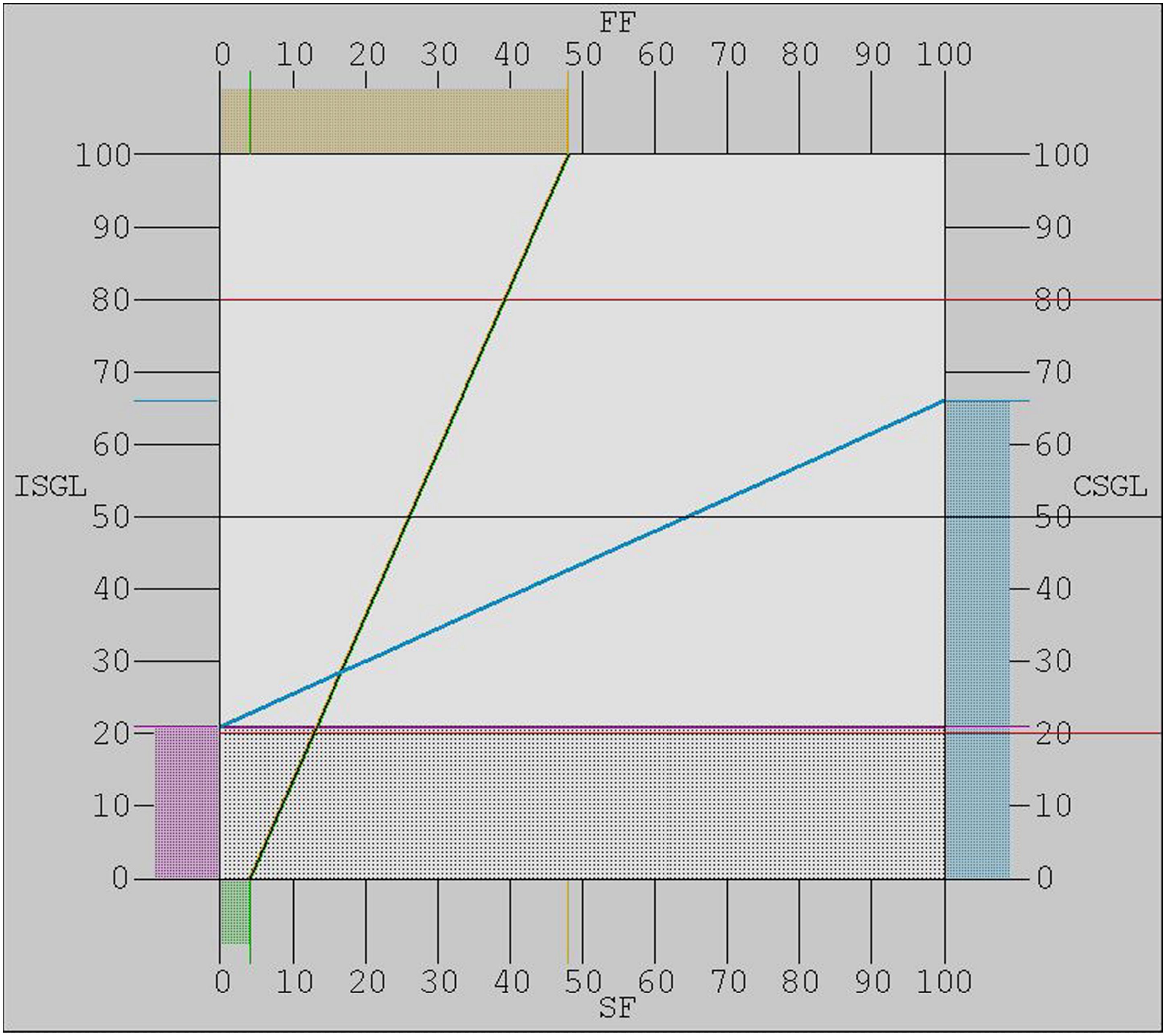

Figure 5. The compensated configural display. This display adds a calculated variable (compensated level) to the baseline display.

for compensated level, and 2) a line connecting compensated level to indicated level.

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Insert Figure 6 about here

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Evaluation

These four displays were evaluated using several different methodologies. The participants controlled the rate of feed flow with the goal of bringing indicated level to a target value (50%) as quickly as possible and then maintaining indicated level as close to the target value as possible. On a low percentage of trials two types of faults (either a steam generator leak or a stuck valve) could occur. Throughout all trials participants were periodically asked to provide fault estimates using a seven-point scale. It was predicted that both forms of aiding would improve performance at these control and fault detection tasks.

Participants also completed information probes that required them to provide quantitative estimates of either low-level data (individual variables) or high-level properties (relationships between variables). There were two categories of high-level property probes: well-mapped and poorly-mapped. Well-mapped probes had a direct visual correlate between properties in the domain and graphical features in the display while poorly-mapped probes did not. The goal of these evaluations was to assess the extent to which the display manipulations influenced the participants' basic capability to obtain information from the various displays. In particular, we were interested in determining whether or not the additional visual information associated with the time tunnel design technique resulted in visual clutter that produced a negative impact on this basic capability.

Method

Participants. Eight graduate students (5 men and 3 women) from Wright State University participated in the experiment and were paid $5.00 an hour. The participants' ages ranged from 20 to 32 years of age and they had normal or normal-corrected vision with no color-blindness deficiencies.

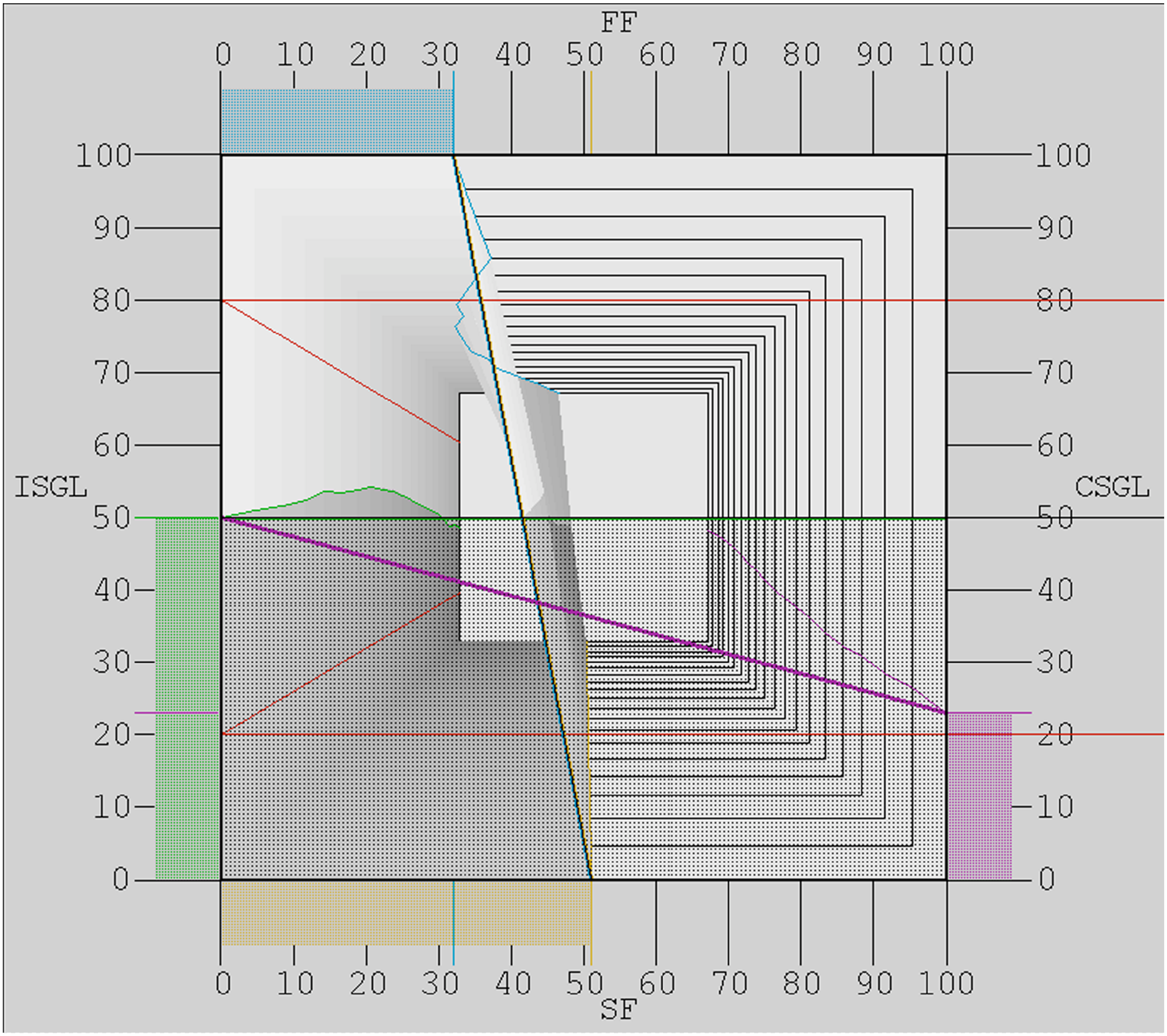

Figure 6. The combined configural display. This display combines the time tunnel concept and compensated level.

All individuals had participated in at least 2 similar experiments with a minimum of 20 hours of experience.

Apparatus. All experimental events were controlled by a general purpose laboratory computer (Sun Microsystem 4-110 Workstation) located in an enclosed experimental room. A color video monitor (40.64 cm, 1152 by 900 resolution) and a standard keyboard were used.

Simulation model. For a more detailed description of the simulation model see Bennett, Toms, and Woods [18].

Stimuli. Four displays were evaluated. The baseline and compensated displays are illustrated in Fig. 2 and 5, respectively. The plotting area formed by the x- and y- axes measured 12.70 cm high by 12.70 cm wide and was off-white in color. The larger plotting area containing axes and variable labels was 18.01 cm by 20.32 cm (medium gray). The entire window was 22.00 cm by 26.80 cm (dark gray). Each bar graph was 12.70 cm (maximum height) by 1.18 cm. The bar graphs used a "stencil" with every other pixel retaining the background color. For each functionally-related pair of variables a redundant graphical marker was superimposed on the bar graph (i.e., the steam flow bar graph and a feed flow marker appeared at the bottom of the display). The plotting area underneath the current value of indicated level also used a stencil (every third pixel, black). The trip set points were dull red; the target indicated level was white (appears black in figures). All graphical information (e.g., bar graphs, perspective trends) pertaining to an individual variable (e.g., steam flow) were color-coded using one of four codes (green, purple, blue, and mustard).

The tunnel and combined displays are illustrated in Fig. 4 and 6, respectively. The perspective grid was constructed using the assumptions outlined in the introduction.

Procedure. Each participant completed 2 practice sessions (1 h) and 8 experimental sessions (1 h). In the first practice session the participants were given descriptions of the displays, the tasks, and experimental instructions. No discussion of specific control strategies was ever provided. The participants were tested individually in an enclosed room. There were 8 non-fault trials per experimental session (4 displays and 2 repetitions). The presentation order was random. Each trial lasted for 5 minutes. Steam flow and feed flow were 0% initially; indicated level and compensated level were 35% initially. Every two seconds a 1% increase could occur in steam flow (25% probability) as long as steam flow was less than 80%. The displays were also updated every 2 sec. Participants changed feed flow by pointing and clicking on one of four boxes (increasing or decreasing feed flow by 1% or 4%, see Fig. 2). They were instructed to provide control inputs that moved indicated level to a target level (50%) quickly, to maintain indicated level close to this target level, and to avoid crossing set point boundaries. Auditory feedback (four tones) occurred when a boundary was crossed. Continuously-updated root mean square error (RMS) scores were provided.

Two faults could occur. One fault simulated a steam generator leak by decreasing the value of indicated level by 0.25% at 2 sec intervals. The second fault simulated a stuck valve: control input to feed flow caused the display to change (commanded value) but not the simulation (actual value). When a fault was present, it began from 30 to 90 sec into a trial. Participants provided a confidence rating for the presence or absence of a fault at seven points in an experimental session (40, 80, 120, 160, 200, 240, and 280 sec). Participants pointed and clicked at a seven-point scale (see Fig. 2). Feedback on the presence or absence of a fault was provided at the end of each trial. Each participant completed 2 fault trials (1 leak, 1 stuck valve) in each of 8 experimental sessions for a total of 16 fault trials. Each combination of fault type (2) and display type (4) occurred twice for each participant. The experiment-wide presentation order was counter-balanced across participants and days so that each combination of fault type and display type occurred exactly twice on each day. Fault trials occurred within the first eight trials in a session; additional, non-fault trials for those displays were re-administered at the end of the session. Thus, 10 trials were completed in a session (8 non-fault and 2 fault trials).

Three low-level data probes (steam flow, feed flow and indicated level) and three high-level property probes (steam flow vs. feed flow, steam flow vs. indicated level, and feed flow vs. indicated level) were completed during each experimental trial. They occurred in 6 time windows (45-75, 85-115, 125-155, 165-195, 205-235 and 245-275 sec), were administered when the next screen update was scheduled to occur, and appeared in random order. An auditory tone sounded, a description of the probe was presented (e.g., "Enter % value for SF"), and participants entered a numeric value via the keyboard. The display remained visible at all times. The participants were instructed to respond to probes as accurately and quickly as possible. Feedback on both accuracy and latency was provided. A probe was re-administered in the final 25 sec of a trial if the participant entered an unacceptable value or changed their estimate. The color coding for the four variables was counterbalanced across participants.

Results

A similar procedure was followed for the majority of analyses. Outliers were identified using the test described in Lovie [19, p. 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. Outliers were not considered in subsequent analyses. Non-parametric tests (Friedman ANOVA) were conducted to determine if the outlier distribution was random (none were significant). For each dependent measure a minimum of 3 pre-planned, orthogonal contrasts were performed to assess display effects. Tests for simple main effects were conducted when a significant interaction contrast occurred.

Information probes. 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 as it appeared on the screen. Response time was measured from the appearance of the prompt until the first digit of the participant’s response (1/100 second accuracy). Of the 3,840 probes that were administered 100 probes were identified as either accuracy or latency outliers (2.60%).

The pre-planned orthogonal contrasts performed on these data are listed in Table 1. Contrasts 1 through 3 assess the main effect of display and Contrasts 4 through 8 assess the main effect of probe. Contrasts 9 through 23 assess the display by probe interaction. The significant contrasts are listed in the right side of Table 1; the means for probe type are illustrated in Fig. 7. All significant contrasts are considered in the discussion section, with the following exceptions. Low-level data probes were completed with significantly less error and in significantly less time than the high-level property probes (Contrast 4). There were also significant differences between low-level data probes: probes for indicated level were significantly more accurate than probes for feed flow and steam flow (Contrast 5); probes for feed flow were completed in significantly less time than probes for steam flow (Contrast 6).

Control performance. Six measures of control performance were considered. Acquisition time was measured from trial initiation until indicated level first crossed into the target band (45% to 55%). Settling time was measured from trial initiation until indicated level crossed and remained inside the band for the remainder of the trial. Four estimates of control error [20] were considered during a final tracking phase (starting at the average settling time across all participants and ending at trial completion). The formula for root mean square error (RMS) was $\sqrt{\Sigma(X-50)^2/N}$, where X is indicated level for an update and N is the number of updates. The formula for constant position error is $\Sigma(X-50)/N$. The formula for modulus mean error is $\Sigma abs(X-50)/N$. The formula for standard deviation of the error is $\sqrt{\Sigma(X-\bar{X})^2/(N-1)}$, where $\bar{X}$ is the mean value of indicated level across updates. Preliminary analyses revealed that one of the 8 participants was unable to control the system effectively. This individual's acquisition and settling times were approximately twice as long as all other participants. In fact, the average value of indicated level at the end of non-fault control trials was actually outside the target band and was heading away from the target band. An analysis of the qualitative aspects of this individual's performance indicated that effective control strategies (i.e., "swell" control levers) were not employed. As a result, these data were not considered in the analyses of control or fault estimation.

Analyses of control performance for non-fault and reservoir leak fault trials were conducted (the stuck valve fault trials were not analyzed since control input had no effect). Outliers were identified in the non-fault trials for acquisition (10 scores, 2.23%), RMS error (7 scores, 1.56%), constant position error (7 scores, 1.56%), modulus mean error (7 scores, 1.56%), and standard deviation of the error (8 scores, 1.79%) measures. Outliers were identified in the reservoir leak fault trials for settling time (2 scores, 3.57%). The pre-planned contrasts for the main effect of display were conducted for the 6 control measures outlined above. No significant effects were found for reservoir leak faults. The significant contrasts for non-fault trials are listed on the right side of Table 2; the display means are illustrated in Fig. 8. All significant contrasts are described in the discussion section with the following two exceptions. Contrast 2 for acquisition time indicated that performance for the compensated and tunnel displays was significantly better than performance with the combined display. Contrast 3 for acquisition time indicated that performance with the compensated display was significantly better than the tunnel display.

Fault estimates. Trend analyses (linear and quadratic trends) were used to assess variations in fault estimates over the seven measurement intervals that occurred during the course of a trial. Thus, a contrast for linear trend between displays compared differences in line slopes. Eleven orthogonal contrasts were completed for each trend analysis: 3 contrasts to assess the main effect of displays, 2 contrasts to assess main effects of faults, and 6 contrasts to assess the display by fault interaction effect (see Table 3). The same 11 contrasts were also conducted for the latency of fault estimates. Latency was measured from the appearance of the prompt until the participant responded by clicking a check box (1/100 second accuracy). The display means for average estimates are illustrated in Fig. 9.

All significant contrasts are described in the discussion section, with the following exceptions. Participants were able to discriminate between fault and non-fault trials effectively (Contrast 4, linear and quadratic trends). Participants required significantly more time to complete estimates during fault trials (Contrast 4). Contrasts 1, 2, and 3 were significant, but need to be interpreted in light of the higher-order interactions with fault type (see discussion).

Discussion

One goal of the information extraction evaluation was to determine if the time tunnel design technique added visual clutter and compromised an observer's basic capability to obtain information. The pre-planned contrasts revealed only one significant difference between displays: the tunnel display produced significant costs in latency relative to the compensated display (only under certain combinations of conditions -- Table 1, Contrast 15). Thus, it appears that the additional visual information associated with the time tunnel design technique did not degrade information extraction performance in any appreciable fashion.

A second goal was to assess differences in performance that were related to probe type. A key finding was that the well-mapped probes were completed in significantly less time and with significantly more accuracy (Table 1, Contrast 7) than the poorly-mapped probes (the means are illustrated in Fig. 7). For well-mapped probes there was an emergent visual feature (the mass balance indicator line) that corresponded directly to the property of interest. This was not the case for the poorly-mapped probes, and it is clear that performance suffered accordingly. This particular finding underscores a fundamental guideline in the design of configural displays: the effectiveness of a configural display will be determined by the quality of the mapping between the specific visual properties it contains and the critical domain properties that are represented. These results are consistent with both conceptual analyses [e.g., Bennett & Flach, 10] and empirical findings [e.g., Buttigieg and

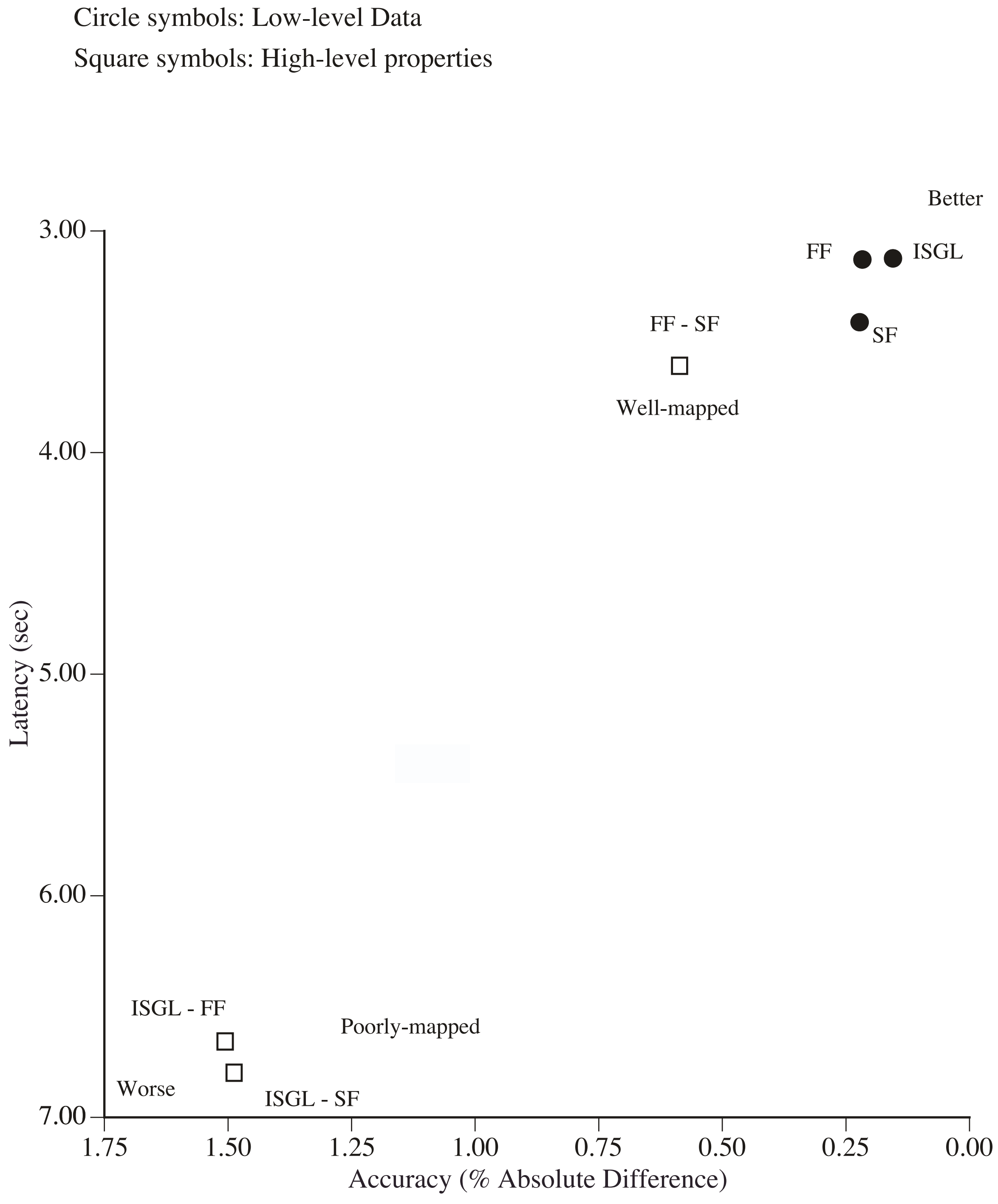

Figure 7. Average latency (in sec) and accuracy (error magnitude) for information probes. Lowlevel data probes (circle symbols) required the participants to report the value of an individual variable (indicated in a steam generator level -- ISGL, feed flow -- FF, and steam flow -- SF). High-level properties (square symbols) required the participant to report differences between variables (FF vs. SF -- well-mapped, ISGL vs. FF and ISGL vs. SF, poorly-mapped).

Sanderson, 21].

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Control measures

The results obtained for the six measures of control indicate that compensated level improved performance at the manual control of feedwater task substantially. Both the general pattern of results (see the means illustrated in Fig. 8) and the pattern of statistical significance (Table 2) are very similar across the various dependent measures and therefore these results will be described concurrently. Contrast 1 indicated that performance with the baseline display was significantly worse than performance for the other three displays (all dependent variables except acquisition time). Contrast 2 indicated that performance with the combined display was significantly better than the average performance obtained with the compensated and tunnel displays (root mean square, modulus mean, and standard deviation). Contrast 3 indicated that performance obtained with the compensated display was significantly better than performance with the tunnel display (settling time, root mean square, modulus mean, and standard deviation). Thus, participants maintained indicated level within the target band more efficiently, kept the value of indicated level closer to the goal value, and did so with less variability with the two displays that contained compensated level (compensated and combined displays).

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Fault detection measures

The results obtained for measures of fault detection (Table 3) revealed a similar pattern. Fig. 9 illustrates the average fault estimates (and the associated quadratic trend lines) obtained for each

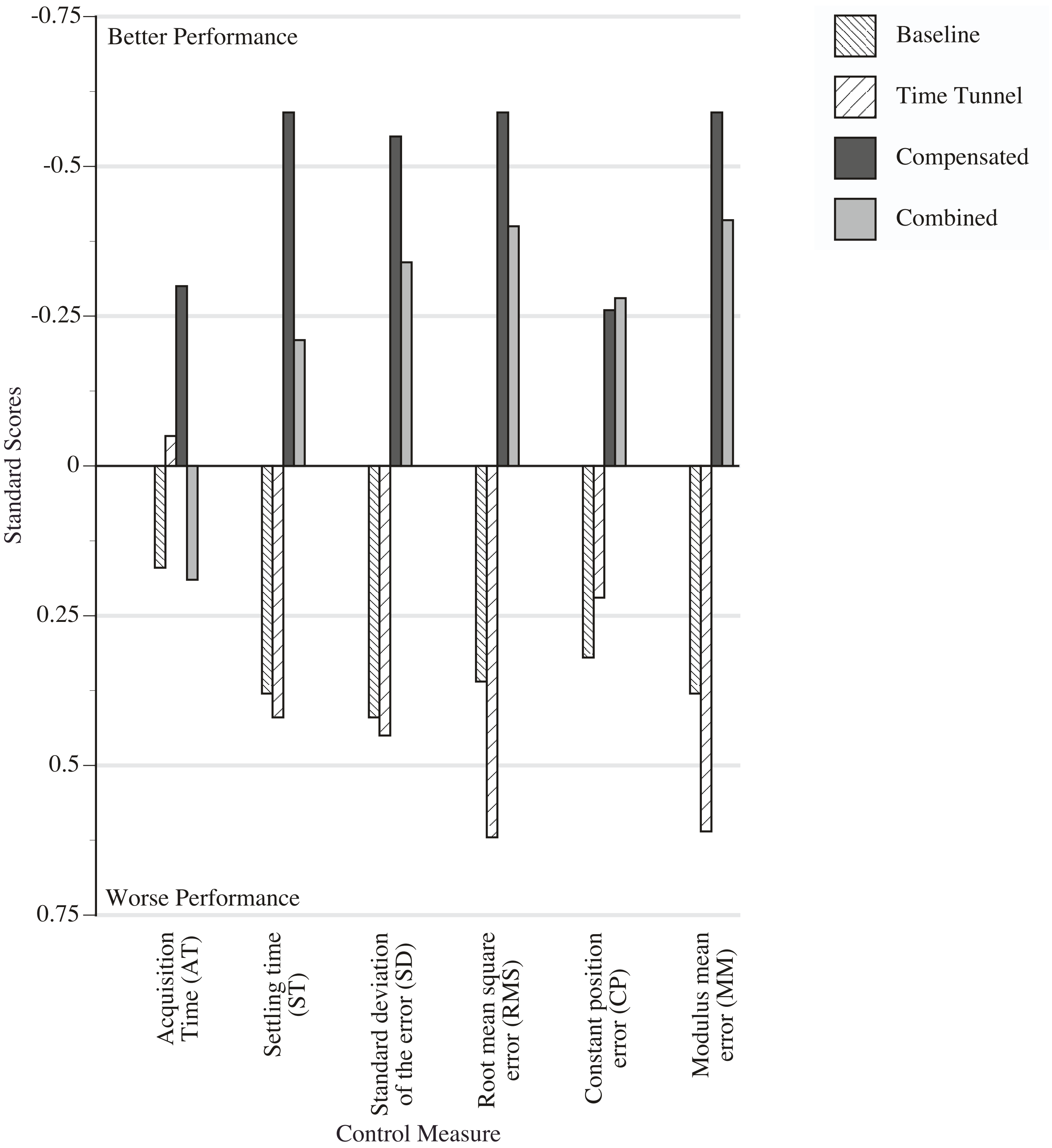

Figure 8. Average control performance for each dependent measure and each display during nonfault trials.

display as a function of time into trial. The estimates obtained with the compensated and combined displays (square symbols, dotted lines) were lower than those obtained with the baseline and tunnel displays (circle symbols, solid lines) during the non-fault trials (Fig. 9, left graph). In contrast, these two displays produced estimates that were substantially higher when a fault was present (Fig. 9, right two graphs), particularly during the early and middle portions of a trial. This suggests that the two displays containing compensated level increased participants sensitivity to the presence of faults and therefore allowed them to differentiate between fault and non-fault trials more effectively.

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The statistical analyses support these conclusions. Fault detection performance was significantly worse with the baseline display when compared to the other three displays (Contrast 6, linear and quadratic trends). During fault trials participants were less certain that a fault was present with the baseline display than with the other three displays, especially as time into trial increased. In contrast, during non-fault trials participants were more certain that a fault was present with the baseline display. These performance advantages were not due to the tunnel display. The combined performance of the tunnel and compensated displays was significantly worse than performance with the combined display (Contrast 8, quadratic trend); the tunnel display produced significantly poorer fault detection performance than the compensated display (Contrast 10, quadratic trend). Thus, compensated level clearly improved the participants capability to detect the presence of faults in the system.

General Discussion

The results indicate that compensated level was very effective in improving system control and fault detection performance. The development of this form of calculation aiding was based upon detailed analyses of the manual control task involving plant operators and other subject matter experts [15]. Compensated level provides an estimate of indicated level that separates the normally con-

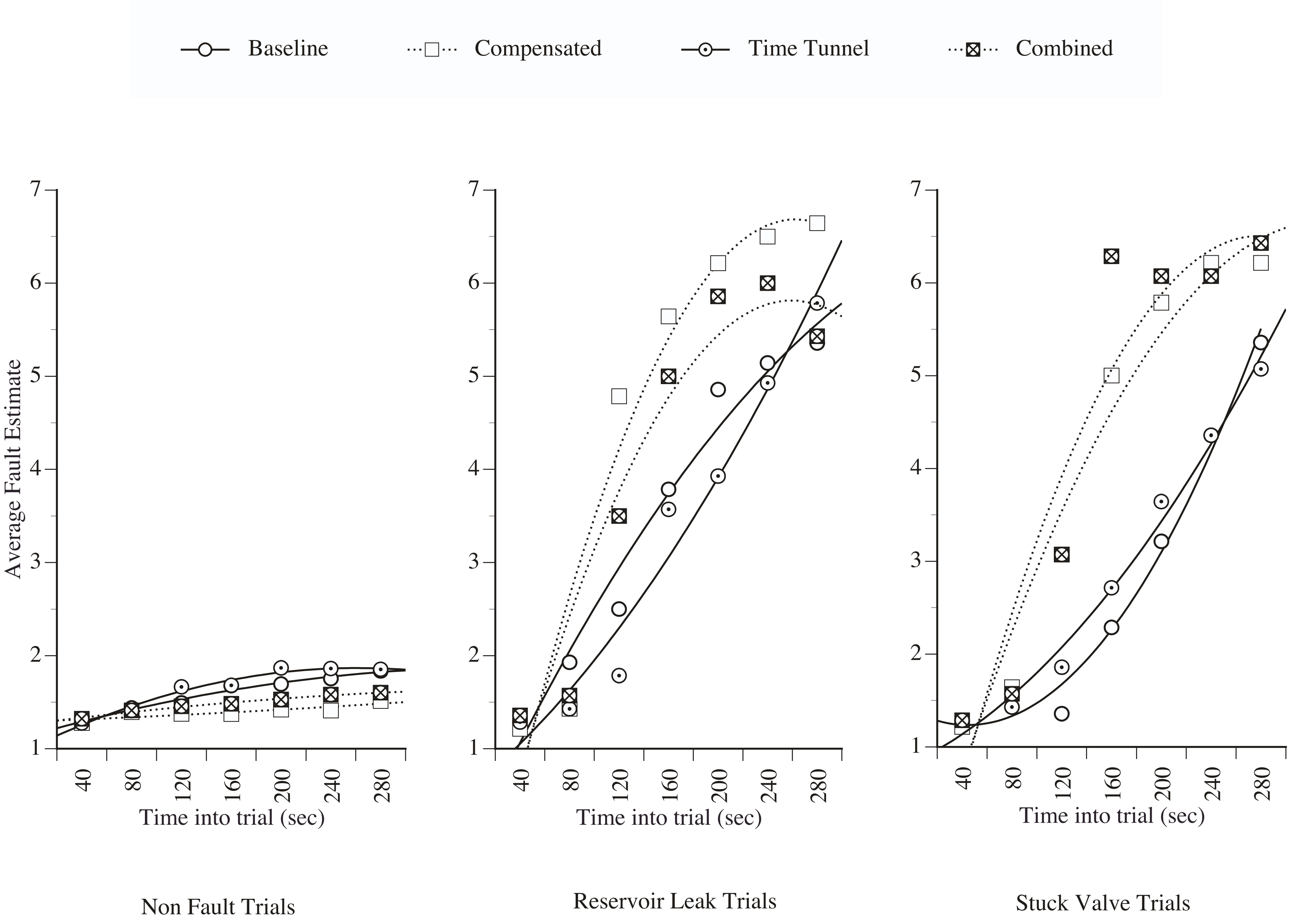

Figure 9. Average fault estimates for each display and each estimate interval (time into trial). Estimates for non-fault, reservoir leak fault and stuck valve trials appear in the left, middle and right graph, respectively.

founded contributions of mass and energy (i.e., removes the counter-intuitive, time delayed behavior of indicated level). As a result, compensated level improves control performance because it allows indicated level (the critical variable) to be controlled much more directly and with considerably less cognitive effort. The results for fault detection also indicate that it provides an effective context for determining when the system constraints have been broken.

In contrast, the representation aiding evaluated in the present experiment was not effective. There is very little evidence that the time tunnel concept improved performance at either the system control or fault detection tasks. There are at least three explanations of why the current assessment of the time tunnels display concept was not found to be effective and each possibility will be described in greater detail.

The first explanation is that temporal information (i.e., the value of system variables over time) may not, in and of itself, be critical for effective performance. There are good reasons to believe that this explanation is not a tenable one. Yet despite the logical and intuitive appeal, findings like those obtained in the present study are not uncommon. There is mixed empirical evidence with regard to the effectiveness of displays that portray historical information [11, 12, 22].

The second explanation is that our implementation of the time tunnel display concept was not an effective one. Bennett, Payne, and Walters [23] tested this explanation by implementing an alternative version of the time tunnel display that simplified the visual information provided in the display (see Fig. 10). The primary differences were the modification of the perspective grid (removal of wire frame and constant gray-scale coding) and the mass balance indicator (replacement of furling "sheet" with simple connecting lines). However, the ensuing evaluation revealed that the redesign did not change the general pattern of results that were obtained.

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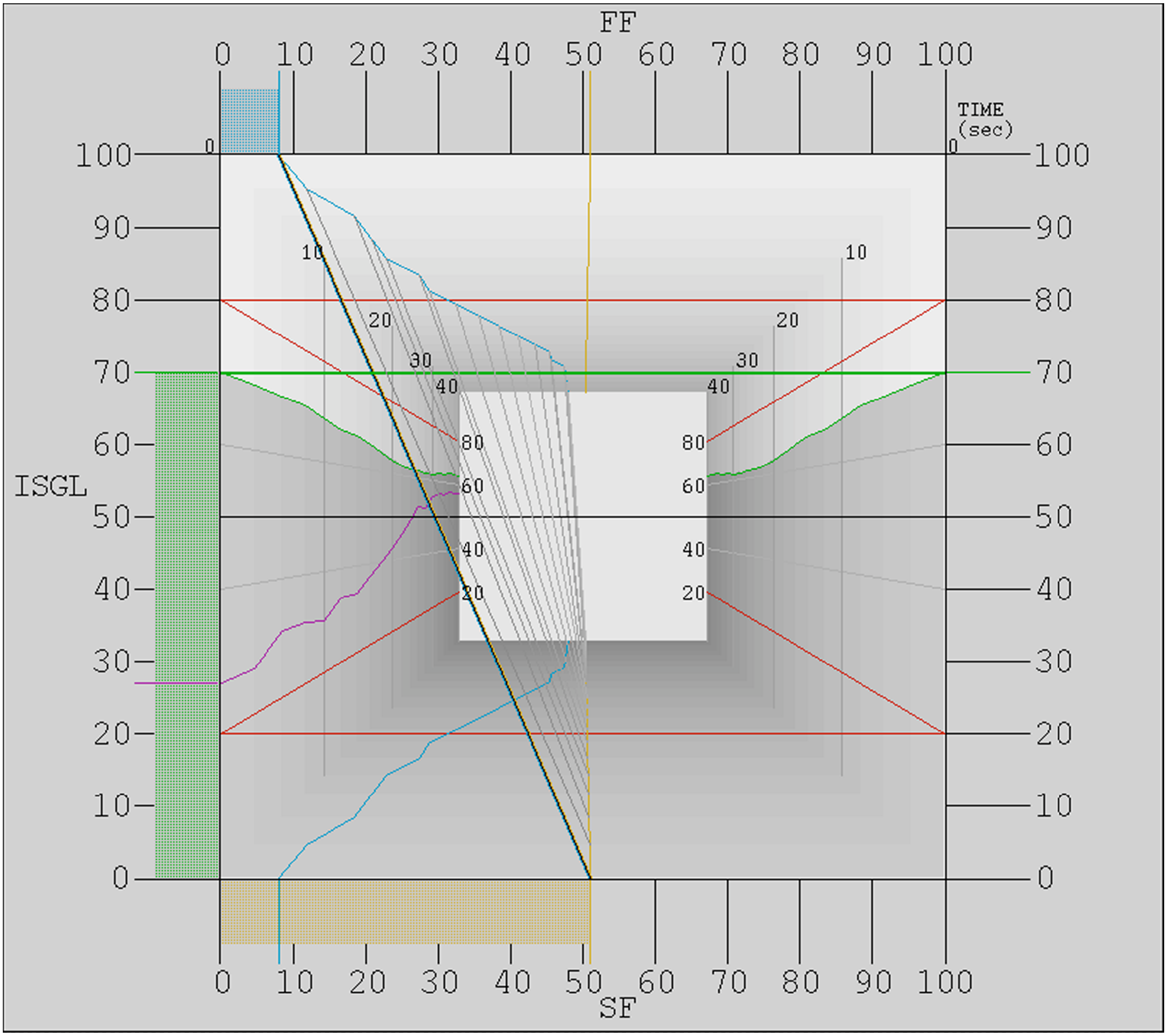

Figure 10. Alternative design of time tunnel display.

A third explanation is that both the concept and the implementation are actually effective and that some other factor(s) are responsible for the lack of performance benefits. One possibility is that the methodology we used in our experiments created a situation where the temporal information contained in the display did not need to be considered to perform the tasks effectively. More specifically, it is possible that the participants were able to internalize the relevant temporal information and to use this internalized information rather than the externalized information encoded with the time tunnels design technique. Several factors may have contributed to this possibility: the basic task was not varied extensively, the participants had a great deal of experience at the task, and there were no secondary tasks to perform. If this explanation is true, then any external representation would be superfluous. Quite simply, the time tunnel display might not have proved effective because it did not provide the participants with any information that they were not already aware of.

A second study conducted by Bennett et al. [23] investigated this possibility by changing the experimental methodology. Rather than controlling and monitoring the part task simulation in real-time the participants were presented with "snap-shots" of various system states and asked to perform three tasks: 1) fault detection, 2) fault identification, and 3) state estimation. These snap-shots were actual system states (depicting fault and matched non-fault conditions) that the same participants had generated in the first experiment. Three displays were evaluated. Two displays (the baseline display and the tunnel display) were the same displays in Exp. 1. A third display combined the baseline display and a traditional trend display. The results indicate that the two displays containing temporal information about prior system states (i.e., the tunnel and the trend display) significantly improved performance relative to the baseline display. In addition, there was considerable evidence that the tunnel display was significantly more effective than the trend display. The results were particularly evident for state estimation (i.e., estimating compensated level).

Summary

The results of present experiment are not particularly encouraging for the time tunnels display design technique. Both control performance and fault detection performance with the time tunnel display was significantly less effective than performance with the displays containing compensated level. This finding, in and of itself, is not viewed as being particularly problematic. The compensated level variable is one of the primary end products of an extensive research and development effort [15] aimed at improving performance at the manual control of feedwater task. It was specifically designed to resolve those aspects that make the task difficult (i.e., it parcels out the counter-intuitive and time-delayed thermodynamic effects on indicated level). Previous research has indicated that this class of calculated variable (i.e., quickened displays) is very effective [16]. On the other hand, the lack of performance benefits relative to the baseline display are problematic.

Subsequent evaluations have proven more positive and indicate that methodological considerations may have played a major role in the lack of performance benefits. Bennett et al.'s [23] finding that participants estimated the value of compensated level more effectively with the time tunnels display than with either the baseline display or a traditional trend display is particularly noteworthy. In combination with the results of the present experiment, these findings suggest that the time tunnels display design technique could also improve performance at control and fault detection tasks in real-time, given an appropriate evaluative setting. The mixed results of other researchers who have evaluated other forms of temporal information [11, 12, 22] indicate that devising this evaluative setting will be a challenge.

We believe that the time-tunnel display concept is worthy of the additional research effort required to sort out these issues. It offers several potential advantages over traditional displays. Configural displays can be effective, but typically show only current values. Configural representations of critical system values and properties over time can be provided when the time tunnel display concept is applied to configural displays. This solution provides one centralized representation for both current and historical information, as opposed to two different representations that may be separated in space and may have different geometrical formats. This will reduce the physical effort required for locating information, the cognitive effort in maintaining and integrating this information, and provide a more economical use of valuable display "real estate." Also, unlike quickened displays and other forms of calculation support, it is a general approach that will not require extensive research and development for implementation in a wide variety of application domains.

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Figure Captions

Figure 1. The time tunnel display concept as introduced by Hansen [12]. System states that occurred previously in time are presented in the depth plane as successive distortions of four-sided geometrical forms that are scaled according to the laws of perspective geometry.

Figure 2. The baseline configural display. This display represents key variables in the manual control of feedwater task which include the indicated level in a steam generator (ISGL), the rate of mass flowing into (feed flow -- FF) and out of (steam flow -- SF) a steam generator, and the property of mass balance (i.e., the difference between steam flow and feed flow).

Figure 3. A simplified version of the time tunnel display concept as implemented in the current experiment. A perspective grid is formed using perspective geometry which is then used as a framework to plot system variables across time.

Figure 4. The time tunnel configural display. This display adds gray-scale shading to the perspective grid, thereby emphasizing the tunnel metaphor and critical data relationships (i.e., mass balance over time).

Figure 5. The compensated configural display. This display adds a calculated variable (compensated

level) to the baseline display.

Figure 6. The combined configural display. This display combines the time tunnel concept and compensated level.

Figure 7. Average latency (in sec) and accuracy (error magnitude) for information probes. Low-level data probes (circle symbols) required the participants to report the value of an individual variable (indicated in a steam generator level -- ISGL, feed flow -- FF, and steam flow -- SF). High-level properties (square symbols) required the participant to report differences between variables (FF vs. SF -- well-mapped, ISGL vs. FF and ISGL vs. SF, poorly-mapped).

Figure 8. Average control performance for each dependent measure and each display during non-fault trials.

Figure 9. Average fault estimates for each display and each estimate interval (time into trial). Estimates for non-fault, reservoir leak fault and stuck valve trials appear in the left, middle and right graph, respectively.

Figure 10. Alternative design of time tunnel display.

Table 1: Pre-planned orthogonal contrasts and results for information extraction performance assessment.

		Displays and contrast weights:				Probes and contrast weights:						Dependent Measures F(1,7) p <)	
Contrast #,Verbal description:		Baseline	Compensated	Tunnel	Combined	Indicated Level	Feed Flow	Steam Flow	Feed Flow vs. Steam Flow	Indicated Level vs. Feed Flow	Indicated Level vs. Steam Flow	Accuracy	Latency
Main Effect of Display:													
1.	Baseline vs. Compensated, Tunnel, Combined	3	-1	-1	-1	1	1	1	1	1	1		
2.	Combined vs. Compensated, Tunnel	0	-1	-1	2	1	1	1	1	1	1		
3.	Compensated vs. Tunnel	0	1	-1	0	1	1	1	1	1	1		
Main Effect of Probe:													
4.	Low-level Data vs. High-level Properties	1	1	1	1	1	1	1	-1	-1	-1	0.0003	0.000001
5.	Indicated Level vs. Feed Flow, Steam Flow	1	1	1	1	2	-1	-1	0	0	0	0.05	
6.	Feed Flow vs. Steam Flow	1	1	1	1	0	1	-1	0	0	0		0.0004
7.	Well-mapped vs. poorly-mapped	1	1	1	1	0	0	0	2	-1	-1	0.0007	0.000007
8.	Poorly-mapped vs. poorly-mapped	1	1	1	1	0	0	0	0	1	-1		
Display by Probe Interaction Effect:													
9.	1 x 4	3	-1	-1	-1	1	1	1	-1	-1	-1		
10.	1 x 5	3	-1	-1	-1	2	-1	-1	0	0	0		
11.	1 x 6	3	-1	-1	-1	0	1	-1	0	0	0		
12.	1 x 7	3	-1	-1	-1	0	0	0	2	-1	-1		
13.	1 x 8	3	-1	-1	-1	0	0	0	0	1	-1		
14.	2 x 4	0	-1	-1	2	1	1	1	-1	-1	-1		
15.	2 x 5	0	-1	-1	2	2	-1	-1	0	0	0		0.02
16.	2 x 6	0	-1	-1	2	0	1	-1	0	0	0		
17.	2 x 7	0	-1	-1	2	0	0	0	2	-1	-1		
18.	2 x 8	0	-1	-1	2	0	0	0	0	1	-1		
19.	3 x 4	0	1	-1	0	1	1	1	-1	-1	-1		
20.	3 x 5	0	1	-1	0	2	-1	-1	0	0	0		
21.	3 x 6	0	1	-1	0	0	1	-1	0	0	0		
22.	3 x 7	0	1	-1	0	0	0	0	2	-1	-1		
23.	3 x 8	0	1	-1	0	0	0	0	0	1	-1		

Table 2: Pre-planned orthogonal contrasts and results for control performance in non-fault trials.

	Displays and contrast weights:				Dependent Measures (F(1,6) p <)					
Contrast #,Verbal description:	Baseline	Compensated	Tunnel	Combined	Acquisition Time	Settling Time	Root Mean Square Error	Constant Position Error	Modulus Mean Error	Standard Deviation of the Error
1. Baseline vs. Compensated, Tunnel, Combined	3	-1	-1	-1		0.0006	0.005	0.003	0.003	0.008
2. Combined vs. Compensated, Tunnel	0	1	-1	2	0.02		0.004		0.0002	0.004
3. Compensated vs. Tunnel	0	1	-1	0	0.03	0.0002	0.00003		0.00004	0.000001

Table 3: Pre-planned orthogonal contrasts and results for fault estimate performance assessment

	Displays and contrast weights:				Faults, contrast weights:			Time into trial when estimate occurred, linear and quadratic contrast weights							
Contrast #,Verbal description:	Baseline	Compensated	Tunnel	Combined	Normal	Reservoir Leak	Stuck Valve	40	80	120	160	200	240	280	(F(1,6) p <)
Main Effect of Display:								Linear							
1. Baseline vs. Compensated Tunnel, Combined	3	-1	-1	-1	1	1	1	-3	-2	-1	0	1	2	3	
2. Combined vs. Compensated, Tunnel	0	-1	-1	2	1	1	1	-3	-2	-1	0	1	2	3	
3. Compensated vs. Tunnel	0	1	-1	0	1	1	1	-3	-2	-1	0	1	2	3	0.03
Main Effect of Trial:															
4. Normal Trials vs. Fault Trials	1	1	1	1	2	-1	-1	-3	-2	-1	0	1	2	3	0.000001
5. Fault Trials	1	1	1	1	0	1	-1	-3	-2	-1	0	1	2	3	
Display by Trial Interaction Effect:															
6. 1 x 4	3	-1	-1	-1	2	-1	-1	-3	-2	-1	0	1	2	3	0.03
7. 1 x 5	3	-1	-1	-1	0	1	-1	-3	-2	-1	0	1	2	3	
8. 2 x 4	0	-1	-1	2	2	-1	-1	-3	-2	-1	0	1	2	3	
9. 2 x 5	0	-1	-1	2	0	1	-1	-3	-2	-1	0	1	2	3	0.003
10. 3 x 4	0	1	-1	0	2	-1	-1	-3	-2	-1	0	1	2	3	
11. 3 x 5	0	1	-1	0	0	1	-1	-3	-2	-1	0	1	2	3	
Main Effect of Display:								Quadratic							
1. Baseline vs. Compensated Tunnel, Combined	3	-1	-1	-1	1	1	1	5	0	-3	-4	-3	0	5	0.05
2. Combined vs. Compensated, Tunnel	0	-1	-1	2	1	1	1	5	0	-3	-4	-3	0	5	0.04
3. Compensated vs. Tunnel	0	1	-1	0	1	1	1	5	0	-3	-4	-3	0	5	0.006
Main Effect of Trial:															
4. Normal Trials vs. Fault Trials	1	1	1	1	2	-1	-1	5	0	-3	-4	-3	0	5	0.04
5. Fault Trials	1	1	1	1	0	1	-1	5	0	-3	-4	-3	0	5	
Display by Trial Interaction Effect:															
6. 1 x 4	3	-1	-1	-1	2	-1	-1	5	0	-3	-4	-3	0	5	0.05
7. 1 x 5	3	-1	-1	-1	2	-1	-1	5	0	-3	-4	-3	0	5	
8. 2 x 4	0	-1	-1	2	2	-1	-1	5	0	-3	-4	-3	0	5	0.03
9. 2 x 5	0	-1	-1	2	2	-1	-1	5	0	-3	-4	-3	0	5	
10. 3 x 4	0	1	-1	0	2	-1	-1	5	0	-3	-4	-3	0	5	0.004
11. 3 x 5	0	1	-1	0	2	-1	-1	5	0	-3	-4	-3	0	5	