SUPPORTING OPERATOR SITUATION AWARENESS WITH OVERVIEW DISPLAYS: A SERIES OF STUDIES ON INFORMATION VS. VISUALIZATION REQUIREMENTS

Dal Vernon C. Reising¹, Jason Laberge², & Peter Bullemer¹

¹Human Centered Solutions, LLC, ²Honeywell ACS Labs, Minneapolis, MN

Two prominent trends in the process control industries are (a) supporting operator situation awareness (SA) and (b) installation of large screen technologies. However, simply installing large screen hardware is not a “Field of Dreams” where “if you build it, [situation awareness] will come”. The Abnormal Situation Management® (ASM®) Consortium has conducted a series of studies on effective design of span-of-control overview displays that investigated analysis methods to identify critical information requirements and also effective visualization techniques for those requirements, both combined for the purpose of supporting operator SA. As part of this research, the Consortium conducted controlled evaluations with professional operators to demonstrate improved support of operator SA. This paper summarizes four studies conducted by the Consortium to that end.

Introduction

Operator situational awareness (SA) is an increasingly popular buzzword in the hydrocarbon processing industries. Often, the concern for operator SA focuses on the distributed control system (DCS) display design, and in particular, on whether or not there is a span-of-control (SOC) overview display¹ for that console operator position. One of the laments often heard from operators who had run plants with the older, pneumatic panel boards and are now using a DCS is that they lost the ability to get a sense of where the process was, at a glance, from simply scanning the panel. One of the notions behind the ASM Consortium’s concept of a SOC overview display is to bring back that at-a-glance SA in our modern DCS platforms (Bullemer et al, 2008).

Philosophy of Overview Display Design

During steady, normal operations, an effectively designed overview display will direct an operator’s attention to deviations or movement in the process, before alarm limits are reached. During an upset or process disturbance, the same effectively designed overview
display will help the operator “keep an eye on” the critical parameters for his other equipment areas not directly involved in the disturbance. Thus, the “big picture” is always available while the operator is using the other DCS process displays to focus on the details of the upset. Moreover, if designed effectively, this same overview display should support “at-a-glance” monitoring overall. To support such monitoring, the graphical display objects should be designed to enable ‘direct perception’ of process status (Bennett & Flach, 1992; Bullemer & Reising, 2008).

To recognize that an abnormal situation exists, it is essential for operators to maintain good SA during process monitoring. SA is defined as a person’s “perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (Endsley, 1988, p. 97). Overview displays, then, should support SA by enabling the detection of change or deviation in the “critical few” process parameters. These “critical few” are those that are vital to understanding the overall process health of those areas under the operator’s SOC.

In that regard, the overview display provides key summary information of a select number of critical parameters that tell the story regarding the health of each of the main process areas under the operator’s SOC. The overview display is NOT showing the operator what to do but rather where to look for more information to determine what to do. This is consistent with the ASM Guidelines document Effective Operator Display Design (Bullemer et al, 2008), which states as the first guideline that a SOC overview display should be used. The guidelines indicate that an effective operator console will distribute information across a multi-level display hierarchy (Bullemer et al, 2008). The Level 1 (or overview) display is designed to primarily orient an operator to the existence, severity, location and direction of process deviations. Level 2, 3, and 4 displays are more focused and detailed displays that help operators delve deeper in to problems and take corrective action after they recognize that a problem exists (see Bullemer et al., 2008).

Readers should not misinterpret “detection of deviation” to necessarily mean a negative consequence, and therefore assume that visual alarm annunciation is adequate support for SA. Deviations in critical parameters could also indicate improvements in the process as well, depending on where the process was previously. Visual alarm annunciation alone tends to drive “reactive”, rather than proactive, operator behaviour. Visualizations that show process state, its relation to important limits, the rate of change, and so on, should provide a better foundation for supporting operator SA than “binary” visual indicators (e.g., on / off states). Alarm systems in and of themselves are not a substitute for supporting operator SA because these alarm systems often fail to support the understanding and predicting stages of SA (Endsley, 1995), and only support the perceiving of limit violations.

ASM Consortium Research on Overview Display Design

The ASM Consortium research program has focused on the design of more effective ways to present information to the console operator. Early work included the operator interface framework prototyped during the U.S. NIST-funded “AEGIS” (Abnormal Event Guidance & Information System) program in the late ’90s (Bullemer, Cochran, Harp, & Miller, 1999). The AEGIS operator interface research, taken together with Consortium member site practices, resulted in the guidelines (Bullemer et al, 2008) to use overview
displays and a display hierarchy, both of which support an operator’s problem solving behaviour at different levels of abstraction (Rasmussen, 1986).

Also in the late ‘90s, the Consortium investigated the application of Ecological Interface Design (EID: Vicente & Rasmussen, 1990) as the basis for display design (Jamieson, 2002; Jamieson & Vicente, 2001). A subsequent EID study by Jamieson, Ho, and Reising (2003) documented the design rationale for creating advanced visualizations that allowed operators to directly see the state of their process and equipment. The EID work, at the time that it was performed, was perceived by Consortium members to be a very labour-intensive, equipment-specific, and too complex, all of which are significant barriers for deployment. Since this earlier ASM work, the general human factors literature has produced additional examples of graphical object design to support SA. In particular, Burns and Hajdukiewicz (2004) was an early attempt at creating guidelines for designing such direct-perception, graphical objects.

In 2005, the Consortium conducted a survey of console and operator interface design practices across numerous operating sites under the moniker of “the Operator Cockpit”. One focus of the Operator Cockpit survey was to what extent sites had and were using overview displays. Bullemer and Reising (2008) briefly discussed the general findings with respect to overview displays. In particular, if a console position did have an overview display available, the operators rarely reported using the display. In some cases, the overview display was actually being shown on a screen, but operators said that they did not use it, would rather use the monitor for another more informative display, or that they looked at only a couple of the DCS points in the overview display. In other cases, the overview display was not even shown on a screen (operators had essentially replaced it with other displays they felt were more useful). There were examples of useful overview displays, but that finding was not the norm. In many cases, operators said that the DCS points in the overview display were ‘for the [engineer/supervisor]’ or were ‘what our [engineer/supervisor] thought was important’.

Interaction Requirements (IR) Analysis vs. Visualization Requirements
Prior to the Operator Cockpit initiative, the ASM Consortium had completed work (Bullemer, Reising, & Jones, 1998) on illustrating the use of common requirements analysis methods, such as contextual inquiry (Holtzblatt & Beyer, 1996), scenario-based design (Carroll, 1995), and cognitive work analysis (Vicente, 1999). While this work was not focused exclusively on the design of overview displays, the report provided guidance on which methods were most applicable for overview display design. The objective of using these methods for overview display design was two-fold: (i) identify what the critical variables were for inclusion in the overview display—overcoming several of the short-comings noted above by operators in the Operator Cockpit survey, and (ii) identify what the operational concern, decision criteria, and/or mental operations operators performing on those variables. The remaining step then for designing an effective overview display is identifying the most effective visualization technique with which to display the variable(s) to support the second objective. Bullemer and Reising (2008) discuss these three steps in more detail.

Current ASM Consortium Research Series on Overview Display Design
The ASM Consortium has undertaken a series of studies to illustrate the use and additional value of both the IR methods for identifying critical variables for overview
displays and effective visualization techniques for overview displays. The first study was a design effort to create new display objects that addressed visualization requirements. The second study was a usability pilot that evaluated the usefulness of an overview display designed with both the IR method and new display objects. The third study evaluated the display objects against typical industry-standard shapes (i.e., numerical indicators) for the same set of critical tags. The fourth study will evaluate the value of using the IR method, compared to typical industry practice (“Traditional”), for identifying critical variables.

**Study 1 – Designing Effective Visualization Objects for Overview Displays**

As mentioned above, the perceived obstacles to adopting EID-like visualizations included the monolithic, highly-customized, non-reusable, programming-intensive nature of those integrated visualizations. The Consortium undertook a design study (Bullemer & Reising, 2008) to create equally effective, but arguably more easily deployed, graphical objects with which to design overview displays that would support at-a-glance monitoring of process status and deviations. Graphical gauge objects for typical process parameters, such as temperature, level, flow, pressure, and analyzers were designed for both indicator and controller DCS points. These objects shared a general approach of displaying the process value in the context of other information, such as set point or limit information. In addition, other objects were designed that showed either deviation from a reference value, calculated values, or qualitative trend information. Used in combination, these objects would address the thirteen identified ‘generic’ visualization requirements that were identified (see Bullemer & Reising, 2008 for details). Figure 1(b) below presents an overview display using such qualitative shapes that resulted from Study 1.

**Study 2 – Single-Task Usability Pilot**

A usability pilot was conducted that evaluated the usefulness of an overview display designed with both the IR method and the new display objects. The primary objectives of the usability pilot were to (i) pilot the experiment to determine appropriate study protocols for Study 4, (ii) pilot the SA measurement methods for potential use in Study 4, (iii) analyze usability data to determine metrics to use in Study 4, and (iv) revise the overview display design as required, based on operator feedback.

**Method**

A within-subjects, repeated-measures experimental design was used due to the small number of operators (n=5) available for the study. The primary independent variable was display design (see Figure 1, Qualitative vs. Schematic). The primary task was to monitor the overview display and maintain SA of significant process changes, which were defined as any deviation from normal variability. The SA measurement approach used included three pauses at pre-determined times during a scenario and operators were asked scripted questions about their SA. The operator’s responses were documented in real-time by the experimenter using an a priori recording form.

Operators were seated in front of a 20” monitor where, for each process scenario, the operators viewed a video of the ‘free-run’ scenario for a given display condition. Using videos guaranteed that each operator would experience the same process events, albeit displayed slightly different as a result of the different display conditions. Each upset
scenario was created from historical data and videos of the displays for each scenario were taken while data-pumping the historical data into the displays. Each video had a free-run time of 15 minutes, not including the pauses inserted to administer the SA questions. All operators completed an instruction session, training and practice scenario for the SA monitoring task, and four usability scenarios (2 for each display condition X 2 levels of scenario complexity).

The order that displays were used, including practice, and the order that scenario were completed, was counter-balanced. Scenario complexity was in a fixed order with low complexity scenarios completed first followed by high complexity scenarios.

**Results**

Operator performance measures at each pause included %changes detected, %false responses, a ‘weighted’ SA score, confidence, workload, and usefulness. The weighted SA score normalized the %changes detected as a function of the number of changes to non-changes for a given pause. Because the two display designs differed in terms of the number of DCS points in each, there was a need to normalize the displays in terms of the strength of the signal (i.e., DCS points that changed) relative to the noise (i.e., all other points). Two weighting methods were used wherein the %changes detected were multiplied by (i) optimal beta and (ii) by (1 - signal/noise ratio). Because the Qualitative display condition contained more DCS points overall, and therefore had a lower signal-to-noise ratio, the weighting scheme would increase scores for Qualitative displays. While the weighted SA score may favour the Qualitative display, this display also had a greater potential for generating false responses—that is, incorrect performance.

Due to the small sample size, the Wilcoxon Signed Rank Test was used to analyze the data for display effects. There was a trend for improved Change Detection performance for both scenario complexity conditions when using the Qualitative display (Low: $Z = -1.75$, $p = 0.08$, High: $Z = -1.83$, $p = 0.07$). Similarly, there was a trend for improved Operator performance using the Qualitative display for Low complexity scenarios only when the data was adjusted using the first Weighed SA score ($Z = -1.75$, $p = 0.08$). The second Weighted SA score showed a trend for improved operator performance for both scenario complexity conditions when using the Qualitative display (Low: $Z = -1.75$, $p = 0.08$, High: $Z = -1.75$, $p = 0.08$). Four of the five operators indicated some degree of preference for the Qualitative display. There were no differences between the displays in terms of the other subjective ratings.

**Study 3 – Dual-Task Evaluation of Visualization Methods**

A dual-task experiment using professional operators was conducted to evaluate to what extent different visualizations supported operator SA (Tharanathan et al, 2010). Two overview displays were designed using the IR method mentioned above for a simulated crude unit and naphtha hydrotreater unit. The first display condition used industry-typical numerical indicators (see Figure 1(a)) whereas the second used Study 1’s ‘direct perception’ qualitative objects (see Figure 1(b). Refer to Tharanathan et al (2010) for detailed discussion of display conditions as well as Methods and Results.
Figure 1: Example of overview display using (a) numerical indicators and schematic detail & (b) qualitative display objects

Method
Eighteen operators from several sites participated in the study. Their primary task was to perform a flag matching task (Pringle, 2000). The flag matching task requires spatially remembering the location of two identical flags in a matrix of “covered” flags when only two flags can be uncovered simultaneously. As a secondary task, operators were instructed to simultaneously monitoring the process conditions by watching pre-recorded
videos of each overview display. Four scenarios that represented realistic process upsets were created using two commercial process simulation models and were matched on scenario complexity (low and high). Operators viewed the videos on a Dell Precision M6300 laptop with a 17 inch monitor (resolution = 1280 X 1024). Two scenario sequences were defined with scenario complexity alternating between low and high; the complexity order was counter-balanced within sequence. The pairing of each of the display conditions with the two alternative scenario sequences was counterbalanced.

For monitoring the scenario videos, operators were instructed to speak aloud the name of DCS points that changed, the equipment area on the display where the point was located, and the type of change that occurred (e.g., normal to abnormal). No feedback was provided for secondary monitoring task performance but feedback was provided for the primary task. Operators were also informed that a pause would occur at a random time during the middle of the scenario and also at the end of each scenario. During the pause, the experimenter minimized the overview display and operators responded as accurately as possible to several multiple-choice questions designed to gauge their comprehension of the situation. The pause and multiple-choice assessment approach is a well-known technique for measuring SA accuracy (e.g., Endsley, 1995). Before starting the experimental scenarios, operators completed a practice scenario and were also given screen shots of both displays in steady state as a reference. Each operator session lasted approximately two hours.

Results

There were three dependent variables: (i) Level 1 SA, measured by the number of process changes identified via the operator speak aloud responses, (ii) Level 2 SA, measured by the accuracy of response to the multiple-choice SA questions asked at each pause, and (iii) Primary Task Matches. Three separate 2 (Display: Qualitative, Schematic) x 2 (Complexity: Low, High) parametric repeated-measures ANOVAs were conducted.

Level 1 SA was significantly higher for the Qualitative display compared with Schematic display, F(1,17) = 94.45, p < .0001 and for low complexity scenarios compared with high complexity scenarios, F(1,17) = 81.41, p < .0001. There was also a significant interaction between Display and Complexity, F(1,17) = 14.77, p < .0001. Level 2 SA was significantly higher for the Qualitative display compared with the Schematic display, F(1,17) = 4.74, p < .05. Also, Level 2 SA was significantly higher for the low complexity scenarios compared with the high complexity scenarios, F(1,17) = 12.26, p < .004. The interaction was not significant. For Primary Task Matches, the number of flag matches was significantly higher for the low complexity scenarios, F(1,17) = 10.92, p < .004.

Study 4 – Dual-Task Evaluation of Interaction Requirements Methods

Study 4 is designed to establish the operator performance benefit, if any, that results from using the IR method rather than typical industry practices for identifying variables for an overview display. Moreover, Study 4 is designed to remove a confound present in Study 2, wherein the Qualitative display differed from the Schematic display in terms of both the number of critical variables (DCS points) as well as how those variables were visualized. Study 4 has three display conditions, IR-Qualitative (see Figure 1(b) for similar display), IR-Numerical, and Traditional-Numerical (see Figure 1(a) for similar display). The IR-Numerical contains the same variables as IR-Qualitative, but uses the
numerical indicators as in the Traditional-Numerical to display the process information. Comparing operator SA using the IR-Qualitative vs. IR-Numeric will identify the effect of qualitative visualization. Comparing operator performance between the IR-Numeric and Traditional-Numeric will yield the effects of the additional critical variables identified using the IR method. Comparing the IR-Qualitative and Traditional-Numeric will reveal the interaction between identification and visualization method.

Study 4 is being conducted at the same site as Study 2, but rather than emulating scenarios with historical data only, the scenarios are being driven in part by the site’s high-fidelity simulator model for several of the process units summarized by the overview display. The remaining units not covered by the model are being data-pumped using historical data as before. Because Study 4 is using a simulator, the primary task involves responding to simulated process changes in various units, rather than the flag matching task in Study 3. Moreover, unlike Study 3, the operators participating in Study 4 are intimately familiar with the process units covered by the overview displays, given these operators are qualified operators for that console position.

**Method**
Study 4 is using a within-subject, repeated-measures design similar to Study 2 because of the small number of operators that will be available. Unlike Study 2, this study will use a multiple-choice response format similar to Study 3 to assess SA performance at various pauses during each scenario. Moreover, Study 4 will record primary task performance with respect to responding to process events, such as time to detect the event, time to initiate correct response, and time to reach maximum / minimum process value. To encourage the use of the overview displays—and better position the study to evaluate the usefulness of the overview displays—the audible alarm annunciation will be turned off and the alarm summary display will not be available to operators. As a result, the operators will need to visually monitor the overview displays to detect process changes.

**Results**
At the time of publication, Study 4 was not yet completed. If possible, results will be presented at the conference.

**Conclusion**
In summary, the series of studies indicate that qualitative, direct perception shapes in overview displays better support operator SA compared to traditional schematic displays that use numeric indicators for process values. In particular, operators using the schematic displays never scored above 15% detection of process deviations even with low complexity scenarios, whereas operators using the qualitative display scored over 40% detection of deviations with low complexity displays. While this 40% detection may seem lower than what we would want operator performance to be, this 40% performance level was accomplished despite low familiarity with the qualitative display, its shapes, and the process dynamics it was summarizing. Moreover, given operators in Study 3 were dividing their attention between the primary task and the secondary task of monitoring this qualitative display, the results become more pragmatically convincing.

The relative contribution of the IR method for identifying critical variables versus the qualitative shapes alone is not as clear from the two completed studies. Study 2 compared
an overview display designed with both the IR method and new shapes to a display designed with traditional variable identification and display shapes, and consequently did not isolate the two design contributions. Study 3 on the other hand compared two displays that used the IR method to identify the variables and differed only in the visualization of those variables. Study 4 should be in a better position to ‘isolate’ the contribution of the IR method to operator SA performance. Whether greater performance improvements are facilitated by the IR method, the qualitative display shapes, or the combination of the two is not precisely clear, the overall conclusions suggest that overview displays as promoted by the ASM Consortium guidelines (Bullemer et al, 2008), if designed properly, will lead to improved operator SA and monitoring performance.

Acknowledgements

The series of studies were funded by the ASM® Consortium, a Honeywell-led research and development consortium. Abnormal Situation Management and ASM are registered trademarks of Honeywell International, Inc. The authors would like to acknowledge the contributions of the numerous team members across these ASM Consortium projects, specifically Jeff Sommers, Jamie Errington, Anand Tharanthan, and Rich McLain. The authors would also like to acknowledge the contribution of operators at the ASM member refineries who volunteered to participate in these studies. Finally, we would like to thank George Gabaldon and Patrick Stuer for their assistance in completing these studies.

Endnotes

1 Often the software-instantiated overview display is confused with the (large) screen hardware on which the display is presented. This paper uses the term “overview display” to refer to the ‘software window’—and information presented in it—shown on a screen, irrespective of its size.

References

Bennett, K. B. and Flach, J. M. 1992, Graphical displays: Implications for divided attention, focused attention, and problem solving, Human Factors, 34, 513-533
Bullemer, P. T. and Reising, D. 2008, Improve operator situation awareness with effective design of overview displays, AM-08-23, Presented at the National Petrochemical and Refiners Association 2008 Annual Meeting, San Diego, CA.
Burns, C. M. and Hajdukiewicz, J. R. 2004, Ecological interface design, (CRC Press, Boca Raton, FL)
Endsley, M. R. 1995, Toward a theory of situation awareness in dynamic systems, Human Factors, 37, 32-64
Pringle, H. L. 2000, The roles of scene characteristics, memory and attentional breadth on the representation of complex real-world scenes, Unpublished doctoral dissertation, (University of Illinois at Urbana-Champaign, IL)
Vicente, K. J. 1999, Cognitive work analysis: Toward safe, productive, and healthy computer-based work, (LEA, Mahwah, NJ)
Vicente, K. J. and Rasmussen, J. 1990, The ecology of human-machine systems II: Mediating "direct perception" in complex work domains, Ecological Psychology, 2, 207-249