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A guide for assessing control room operator performance using speed and accuracy, perceived workload, situation awareness, and eye tracking

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ABSTRACT

In the petrochemical industry, control room operators must address safety-critical alarms and other tasks using complex interfaces. This study developed a guide for assessing human performance using standard human factors measurement tools, and tested the sensitivity of those tools with two interface designs (i.e., gray and black) at three levels of workload (i.e., easy, medium, and difficult). The guide measures human performance through speed and accuracy, perceived workload using two standard instruments (i.e., NASA Task Load Index (NASA-TLX) and Subjective Workload Assessment Technique (SWAT)), situation awareness through the Situation Awareness Global Assessment Technique (SAGAT), and gaze through eye tracking coordinates. Twelve engineering student participants completed one simulation session at each of the three workload levels using one of two interface designs. Workload was manipulated through the number of simulated events (failures) in each session. Overall, the speed and accuracy measures, workload ratings, and eye tracking showed sensitivity to differences in workload level, and situation awareness showed sensitivity to the interaction between workload level and interface type. None of the tools were sensitive to interface type alone. Accuracy was highest under easy workload. Time per failure decreased at higher workload levels. Perceived workload ratings from the SWAT increased as workload increased, but workload ratings from the NASA-TLX were not different across workload levels. When workload increased, situation awareness remained steady for the gray interface but decreased sharply for the black interface, illustrating an interaction effect. Finally, the percentage of time spent looking at different areas of the screen during steady-state periods differed among workload levels. The tools in this guide can be used in the petrochemical industry to make design decisions for control room interfaces when workload levels are a concern.

1. Introduction

Control room operators in the petrochemical industry are required to monitor activity, detect abnormalities, and respond quickly to events occurring in the refinery, pipeline, or other systems. Good interface design enables operators to accomplish their duties efficiently and effectively with minimal errors. Human error is a causal factor in a large proportion of industrial accidents, though it is rarely, if ever, the sole cause of an accident (Sanders and McCormick, 1993). Human error in control room operations has been a major factor in petrochemical industry accidents such as the Texas City refinery explosion (U.S. Chemical Safety and Hazard Investigation Board, 2007) and the Milford Haven refinery explosion (Health and Safety Executive, 1997). Proper design of control room interfaces can minimize the likelihood of these errors. The current study considers operator performance, including speed and accuracy, during alarm resolution combined with performance-shaping factors, including perceived workload, situation awareness (SA), and eye movements, improved interfaces are hypothesized to result in better operator performance, lower workload ratings, and higher levels of SA than poorly designed interfaces. The goal is to develop a guide for evaluating control room interfaces based on these measures.

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2. Background

A history of accidents resulting from human error has increased pressure to incorporate human factors into petrochemical control room design. The National Transportation Safety Board (NTSB) reviewed 13 accidents from 1992 to 2004 and found that some aspect of the Supervisory Control and Data Acquisition (SCADA) systems, including alarms and display formats, contributed significantly to the severity of ten of the accidents (2005). The main issue in most cases was the delay between an operator recognizing a leak and taking action to address the problem.

U.S. federal regulations enacted to improve display design for control rooms include the Pipeline Act of 2006 (United States Congress, 2006) and Federal Regulations 49 CFR parts 192 and 195 from the Pipeline Hazardous Material Safety Administration (PHMSA). These regulations have sections concerning display design, fatigue management, and training requirements for control room operators. However, they do not specify how to determine if a display design is satisfactory.

Industry has also developed standards and design guidelines for alarm systems, display design, and control room management. The Engineering Equipment and Materials Users Association (EEUMA) released “Alarm Systems: A Guide to Design, Management, and Procurement,” which provides guidance on developing alarm systems for industrial processes that are usable, safe, and cost-effective (1999). The American Petroleum Institute (API) and the International Society of Automation (ISA) have developed standards for pipeline and refinery companies, respectively. The API has three sets of standards, API Recommended Practices 1165 for pipeline SCADA displays, 1168 for pipeline control room management, and 1167 for pipeline SCADA alarm management (American Petroleum Institute (API), 2007). These standards address the main issues of graphics design for control rooms identified in the PHMSA regulations.

The International Society of Automation (ISA) developed ISA 18.2 to address alarm system management (American National Standards Institute (ANSI) & ISA, 2009). ISA's HMI standard for process automation systems considers performance shaping factors of the human–machine interface including software-specific variables (e.g., density and redundant coding), operator-specific variables (e.g., fatigue and experience), and the interaction between the operator and the interface (e.g., display and alarm effectiveness) (International Society of Automation (2010)).

While these regulations and standards provide guidelines for developing supervisory control systems that support the pipeline and petrochemical industries, there are several shortcomings that hinder their application in designing interfaces. First, the standards do not specify means to measure performance proactively, a step which could optimize interfaces before adverse events occur. Currently, only review mechanisms (i.e., retrospective measures) are in place to evaluate responses to adverse events. Second, there are no interface design best practices specific to the petrochemical industry, which makes design and evaluation of systems challenging. Finally, while the current standards list many performance-shaping factors, there is no indication of how to assess these factors during interface design. This research represents a first step towards addressing these shortcomings by defining interface designs that promote optimal control room management and associated measures for proactive design evaluation.

The current research develops and verifies the utility of a guide to evaluate interfaces used by control room operators in the petrochemical industry. The guide is a collection of validated human factors assessment tools that are applied specifically to control room interfaces. Ultimately, this guide may be used to evaluate current systems and proposed improvements.

3. Guide development

The performance-measurement guide must be accessible to a wide range of users from designers to control room managers to ensure their displays meet regulatory requirements and industry guidelines. Although the ISA lists over 30 performance-shaping factors (2010), assessing all of these factors simultaneously is impractical due to time limitations in conducting experiments with multiple factors. Still, the industry needs measures to address the cognitive and perceptual processes necessary to operate complex interfaces found in the control room, so the authors focused on four principles in developing the guide for efficient performance assessment.

1. The measures in the guide should be easy to collect and analyze without extensive knowledge of human factors because the intended users may be managers, software developers, or others without formal human factors training.
2. The measures should not require equipment that is difficult to obtain or use, since the guide may be used on-site rather than in a laboratory setting.
3. Human performance should be measured directly through speed and accuracy of operator responses. While additional performance-shaping factors may inform design, the most critical outcomes of any control room design are the time needed and accuracy achieved when completing critical tasks.
4. Performance-shaping factors that can be directly influenced by the interface design are the easiest to change, as opposed to those shaped by the surrounding environment or individual differences. This step is needed to define boundaries on this first version of the guide, although future studies may consider other performance-shaping factors.

Based on these principles, the performance measurement guide follows the major processes that influence operator performance: perceiving relevant information (measured through eye movement), integrating the data in conjunction with task goals (assessed through perceived workload ratings), and predicting future events and system states (assessed through situation awareness measures) (Fig. 1).

3.1. Human performance: speed and accuracy of response

Speed and accuracy are two important measures of human performance. Speed is the time taken by an operator to complete an activity, and accuracy is a measure of either correct steps or errors. Measures of speed and accuracy have been used in evaluations of alarm display designs in the chemical and petrochemical industries as performance indicators (Adhitya et al., 2014; Jamieson, 2007; Laberge et al., 2014).

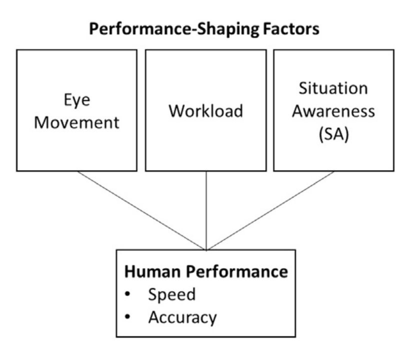

Fig. 1. Integration of performance-shaping factors and performance measurement.