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Review article

Human performance measures for the evaluation of process control human-system interfaces in high-fidelity simulations

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ABSTRACT

We reviewed the available literature on measuring human performance to evaluate human-system interfaces (HSIs), focused on high-fidelity simulations of industrial process control systems, to identify best practices and future directions for research and operations. We searched the available literature and then conducted in-depth review, structured coding, and analysis of 49 articles, which described 42 studies. Human performance measures were classified across six dimensions: task performance, workload, situation awareness, teamwork/collaboration, plant performance, and other cognitive performance indicators. Many studies measured performance in more than one dimension, but few studies addressed more than three dimensions. Only a few measures demonstrated acceptable levels of reliability, validity, and sensitivity in the reviewed studies in this research domain. More research is required to assess the measurement qualities of the commonly used measures. The results can provide guidance to direct future research and practice for human performance measurement in process control HSI design and deployment.

1. Introduction

Process control systems "involve industrial operations for the manufacture or transformation of energy and chemical products in a continuous stream through the interaction of mass and energy" (Moray, 2009). Most operators of modern process control systems work in an environment where plant processes are instrumented and must be monitored and controlled remotely from a control room (Sandom and Harvey, 2004). The operators perceive system information and provide control inputs through a human-system interface (HSI). Thus, HSI design strongly affects operator performance, which is a critical aspect of overall system performance. HSIs for industrial process control are changing dramatically as newly designed facilities incorporate modern digital-based technology. New HSI technology has tremendous potential to improve the quality and safety of these systems. For example, modernized nuclear power plant control rooms have yielded performance improvements (Liu and Li, 2016).

Unintended consequences related to human performance can be introduced by new HSI technologies, especially when human factors and ergonomics (HFE) were not well integrated into the HSI development process (Hendrick, 2002). Process control is a high-risk and high-consequence domain. Human performance issues related to HSI design deficiencies were cited among the causes of many safety-related accidents in the process control industry; examples include the Chernobyl disaster (Stanton, 1996), the Three Mile Island accident (Baber, 1996) and the Texas City Refinery explosion (U.S. Chemical Safety and Hazard Investigation Board, 2007). Thus, the design and evaluation of modern process control HSI technologies must account for the associated human performance issues. Many process control HSI technologies, such as nuclear power control room interface, are one-of-a-kind or first-of-a-kind designs (i.e., they have not been used in other plants). In this situation, it can be more challenging to evaluate how these technologies affect human performance (Hugo and Gertman, 2016).

1.1. Human performance in process control systems

Traditionally, speed and accuracy of observable human actions, typically on the primary task of interest, were considered key

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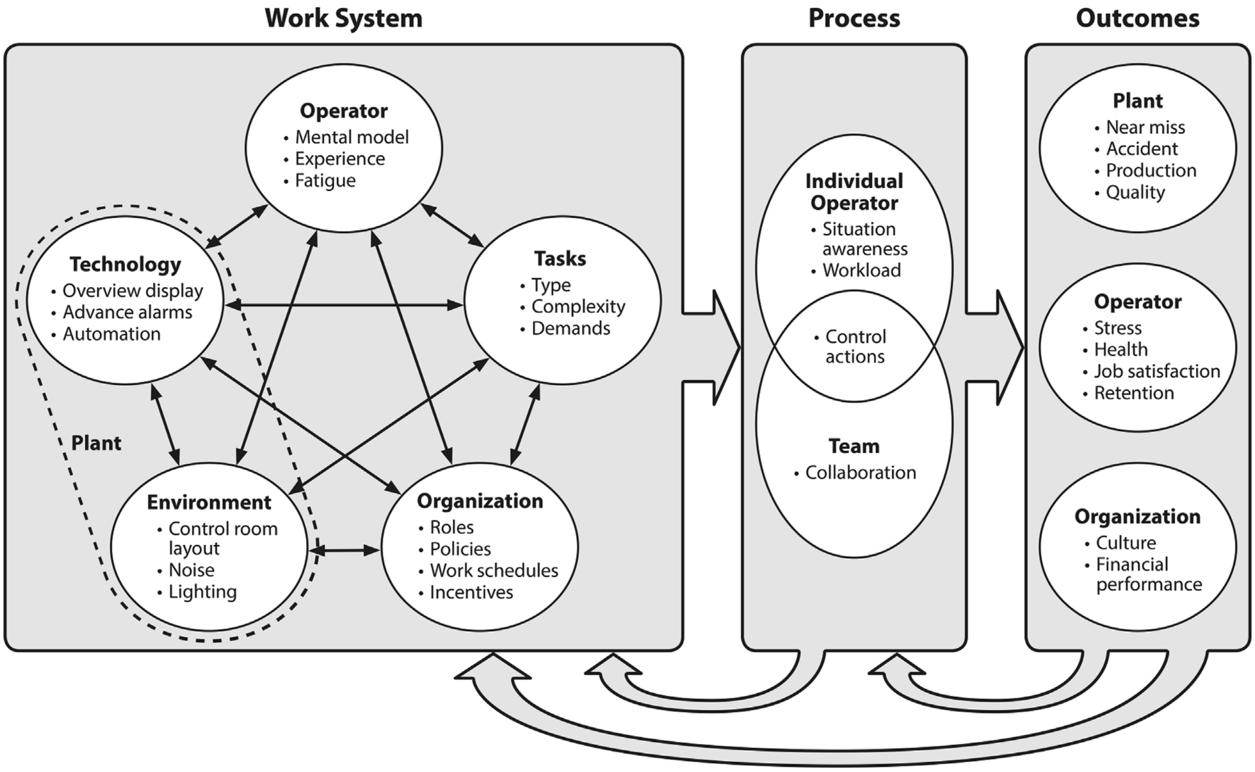

Fig. 1. A conceptual model of a process control system where human performance is part of the transformation process.

performance measures. However, these two measurement types cannot capture latent variables (e.g., workload) that should also be addressed by HSIs. Human performance can be broadly defined as the ability of an operator or a crew to accomplish task requirements (Stanton, 1996). From a systems perspective (Karsh et al., 2006; von Bertalanffy, 1968), human performance must be understood as part of the transformation process between the system's inputs and outputs (Fig. 1).

The input is the sociotechnical work system (Smith and Sainfort, 1989). In process control, the sociotechnical work system includes the following elements: operators (e.g., individual differences, training/experience, psychological state); technology (e.g., automated control, alarm system, overview display); environment (e.g., physical layout, noise, lighting); task (e.g., type, complexity, demands); and organization (e.g., roles, policies, work schedules). System outputs are outcomes related to the plant (e.g., down time, accidents), operators (e.g., occupational health, job satisfaction, job retention), and organization (e.g., culture, financial performance). The transformation process, engaged by human operators, not only includes the operators' physical operations, but also their cognitive, affective, and social processes (Holden et al., 2013).

The introduction of new HSI technology not only affects the technology element of the work system, but also changes the relationship between the technology and other system elements, thereby affecting human performance. An example is the use of new HSIs that integrate automated controls and decision aids. Automation affects the tasks related to information acquisition or analysis, decision-making, and action implementation (Parasuraman et al., 2000). The incorporation of automation can also alter system elements including: operator experience (the operator element), policies (organization), control room layout (environment), and the demand of tasks. New human performance issues, such as over-reliance on automation (Sheridan and Parasuraman, 2005) and difficulty maintaining team situation awareness (Sebok, 2000), can emerge and demand measurement of new dimensions of human performance. In summary, the evaluation of new HSI technologies should (1) capture the full spectrum of human performance to ensure that the HSI meets design requirements without causing negative unintended consequences, and (2) select appropriate measures for all relevant human performance constructs.

1.2. Control room HSI evaluation and high-fidelity simulation

Systematic HSI evaluation, which considers the combined effect of different work system elements on human performance, can be challenging. Traditional usability testing conducted in a laboratory does not account for the complexity of the actual operational environment. Conducting HSI evaluations in the operational environment is usually impractical prior to implementation. Post-implementation performance monitoring can be useful, but by then the correction of problems or design flaws can be prohibitively expensive. The common consequence is additional training to fit the human to the task or technology. High-fidelity simulation is an attractive alternative (Ham et al., 2008; Hollnagel, 2011): First, simulators can accurately replicate most system elements and functions (Liu et al., 2008); thus, providing an ecologically valid test bed for systematic evaluations. Second, high-risk and emergency situations can be simulated, so that human performance in critical event management can be assessed. Third, simulation provides experimental control. For example, in the nuclear power industry, integrated system validation (ISV), which aims to demonstrate that the integration of hardware, software, operating procedures, and personnel supports the safe operation of the plant, is expected to be performed in a high-fidelity simulator, prior to actual system deployment (O'Hara et al., 2012). However, the selection of human performance dimensions and corresponding measures remain issues in high fidelity simulation HSI evaluation studies that would benefit from additional research.

This study aimed to explore the gaps in our understanding of human performance through a systematic review of the existing literature to inform future directions for HFE research and practice. Focusing on control room HSI studies with professional operators working in high-fidelity process control plant simulations, our literature review aimed to answer the following research questions (RQs):