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Eye gaze movement studies of control room operators: A novel approach to improve process safety

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ABSTRACT

Process industries continue to suffer from accidents despite significant regulatory intervention since the mid-1980s. Human error is widely considered to be the major cause for most accidents today. Detailed analysis of various incidents indicates that reduced staffing levels in control rooms and inadequate operator training with complex automation strategies as common reasons for human errors. Therefore, there is a need to develop deeper understanding of human errors as well as strategies to prevent them. However, similar to hardware failures, traditionally human error has been quantified using likelihood approaches; this viewpoint abnegates the role of the cognitive abilities of the operators. Recent studies in other safety critical domains (aviation, health-care) show that operator's level of situation awareness as inferred by eye tracking is a good online indicator of human error. In this work, a novel attempt is made to understand the behavior of the operator in a typical chemical plant control room using the information obtained from eye tracker. Experimental studies conducted on 72 participants reveal that fixation patterns contain signatures about the operators learning and awareness at various situations. Implications of these findings on human error in process plant operations them are discussed.

1. Introduction

Safety and security are of paramount importance in chemical plants as highlighted by President Barack Obama recently labeling them as "stationary weapons of mass destruction" (Obama, 2006). This realization is now at least four decades old, and originally brought out by the disasters at Flixborough, UK (1974), Bhopal, India (1984), and Piper Alpha (1988) among others. Since then, both governments and industry around the world have made numerous interventions to improve process safety. Stringent Process Safety Management regulations are now the norm in most industrialized countries. Today's plants use highly reliable equipment, state-of-the-art automation and control, and deploy sophisticated safety management regimes so as to make accidents rare. Despite these a number of recent accidents including the fires at oil storage facilities in Buncefield, UK (2005) and Jaipur, India (2009), BP's Macondo blowout (2010), Chevron Richmond refinery fire (2012), and the explosion at a fertilizer storage and distribution facility at West, TX (2013) point to the continued need to improve process safety. On a statistical basis, of the 20 accidents that have led to the largest property damage losses in the hydrocarbon industry in the 40 year period from 1974 to 2013, 25% have occurred in the last 5 years from 2009 (Marsh, 2014). Thus process safety is at least as important today as it was in the 1970s and 80s.

A detailed analysis of incidents (Gupta, 2002; Paté-Cornell, 1993; Carson et al., 1992) reveals that human error is one of the principal causes of accidents in the process industries. Statistics show that about 70% of the accidents in process industries are caused by human errors (Mannan, 2004). Some of the reasons that are widely attributed to this include: (i) larger scale and complexity of modern chemical plants with tight mass and energy integrations, (ii) reduction in staffing levels in many control rooms as well as increase in the proportion of relatively inexperienced operators as older operators retire, and (iii) deployment of sophisticated automation and complex automation strategies without a concomitant increase in operations personnel's cognitive ability. Therefore, there is a need to develop deeper understanding of human error in process safety (Mearns et al., 2002; Gordon et al., 2002; Flin et al., 2002) as well as strategies to prevent them.

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The most common approach in practice today to tackle human error is to consider human failure during process hazard analysis. The role of humans in the process and the expected types of human failures are taken into account qualitatively in checklist analysis, HAZOP studies, etc. Quantitatively, human reliability is accounted for using Human Error Probabilities (Swain, 1990) in task-specific risk analysis (Munger et al., 1962; Noroozi et al., 2014). In recent years, there has also been increased effort in accounting for human factors that may impact human failures. Examples of this include designing ergonomic control rooms and user-centered design of human-machine interfaces, as exemplified by the work of the Abnormal Situation Management consortium (Cochran and Bullemer, 1996; Reising et al., 2005). However, less attention has been paid in understanding the cognitive behavior of operators under abnormal situations and real-time interventions to prevent or reduce human error.

Cognitive engineering is a multidisciplinary research area that focuses on analyzing the basic cognitive tasks (such as perception, memory, and reasoning) of human operators to understand their mental workload, decision-making process, planning and situation awareness in industrial settings (Norman, 1986; Parasuraman et al., 2008). As defined by Wilson et al., 2013, "cognitive engineering is the application of cognitive psychology and related disciplines to the design and operation of human–machine systems. Cognitive engineering combines both detailed and close study of the human worker in the actual work context and the study of the worker in more controlled environments." Cognitive engineering studies in many high-risk industries show that human errors typically originate from failures of Situation Assessment (SA) – "the perception of the elements in the environment within a volume of space and time, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1988). In the context of process supervision, SA is the ability to perceive information from the process in order to detect if any abnormality exists and decide on future actions to return the process to a normal or safe state. When an operator is unable to perceive the necessary information required to perform a particular task or if the information perceived is erroneous or incomplete, it impacts the decision making process and leads to unexpected acts on the part of the human operator, as exemplified by the incidents at Three Mile Island (1979), Esso's Longford refinery (1998), and BP's Texas City refinery (2005).

Recent technologies are making it possible to infer the operators' level of SA in real-time. The first step towards SA – perception – manifests itself in the operator's visual attention, i.e., the set of cognitive operations that mediate the selection of relevant information and filtering out irrelevant information (Binder et al., 2009). Human visual attention offers a direct and real-time assessment of SA. Consequently, researchers are now starting to use visual attention measurements such as eye tracking to measure and improve the human's performance in various spheres requiring time-critical decision making such as driving, aviation, surgery, and sports.

In this paper, we explore the potential of eye tracking to measure and understand the *cognitive state* of the *control room operator* during process disturbances. This complements the traditional focus of the Process Systems Engineering community wherein real-time sensor measurements from the process are utilized to understand the *state of the plant equipment*. The rest of the paper is organized as follows. Section 2 presents an overview of eye tracking and its use for studying situation awareness in various domains. We have conducted observational studies of human subjects as they seek to control a simulated chemical process in the face of disturbances. The details of the experimental setup and methodology used in this research is described in Section 3. Results from the experiments reveal that loss of SA and inability of a subject to adequately counter a process disturbance is accompanied by distinct patterns apparent in eye tracking. Evidence of this is presented in the form of illustrative examples in Section 4 and detailed results that lead to this conclusion in Section 5.

2. Eye tracking

The human eye lets light in through the *pupil*, and projects the image on to the *retina* at the back of the eye. The retina contains light-sensitive cells that transduce the incoming light into electrical signals for further processing. The light sensitive cells are not uniformly distributed throughout the retina, rather there is a small area called the *fovea*, where they are over-represented. In order to see a selected object sharply, the eye has to move so that the light from the object falls directly on the fovea. Eye tracking is the process of measuring the motion of the eye relative to the head and inferring the point of gaze – the location on the stimulus object that the subject is looking at.

Research has shown that the movement of the eye contains specific events (Duchowski (2007), Majaranta and Räihä (2002)). Typically, eye movement is segmented into two distinct patterns – fixations and saccades. For example, when reading, the eye temporarily stops at a word and remains still for a period of time. This pause in eye movement is called *fixation* and is necessary to stabilize the image of the word on the retina. Fixations typically last between tens of milliseconds up to several seconds. The eye also rapidly moves from word to word during reading, i.e., from one fixation to another. Such a rapid movement is called a *saccade*. A saccade takes 30–80 ms and could be executed voluntarily or reflexively. Eye movement is measured in visual degrees which can be translated into spatial coordinates (mm or pixels on a computer screen) of the stimulus object based on viewing distance (Groot et al. (1994)). An example of the set of fixations and saccades of a respondent viewing a DCS screen is shown in Fig. 1. In the figure, fixations are shown by dark rectangles (numbers indicating the fixation time in milliseconds) and saccades by straight lines connecting the fixations in the sequence indicated by the numbers on the lines. Besides fixations and saccades, other events in eye movement include smooth pursuit – tracking a slow moving object in order to keep the image stable in the retina, and miniature movements such as tremors, drifts and microsaccades that occur during fixation and help in preventing the fading away of stationary objects.

The history of eye trackers, devices for measuring eye movement, dates back to the late 1800s when they were mostly custom-built, mechanical, and uncomfortable. In recent years, eye trackers have become commercially available, non-intrusive, adequately accurate and robust for widespread adaptation. A variety of eye trackers are available from companies such as Tobii, SR research and SMI systems which offer non-intrusive measurement of observers gaze in a variety of situations (Hermens et al. (2013)). The dominant method of eye tracking relies on video-based measurement of eye movements. A schematic of a typical setup is shown in Fig. 2. Here the eye is illuminated by a pattern of infrared light. The reflected light is captured by a camera and an image of the eye obtained. This image is processed using proprietary image analysis algorithms to estimate a gaze vector. This technique of eye tracking is known as Pupil Center Corneal Reflection (Tobii Technology (2010)). The sampling frequency of the eye tracker, i.e., the number of images acquired and processed per second, is a rough measure of the level of detail that can be observed in the resulting data – higher the frequency, the more detailed eye movement events that can be detected. Typical frequencies today range from about 20 Hz at the low-end to 2000 Hz. The interested reader is referred to Tobii Technology (2010) for a more detailed explanation of the underlying technology in a typical eye tracker.