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Detection tasks in nuclear power plant operation: Vigilance decrement and physiological workload monitoring

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ABSTRACT

Nuclear power plant (NPP) operators perform a variety of tasks that differ in mental workload. These include detection tasks that may be vulnerable to vigilance decrement. The present study used a simulation of NPP operation to investigate possible loss of vigilance during detection. Metrics used to assess operator functioning included subjective measures of workload and stress, physiological indices of workload, and objective performance. Detection, checking and response implementation tasks were compared, in the context of a simulated Emergency Operating Procedure (EOP). Study findings suggested three conclusions. First, detection imposed higher subjective workload and distress than other tasks, but physiological data suggested more complex differences between tasks. Second, vigilance decrements in detection performance were observed within 5-min task 'steps'. However, analyses of physiological metrics suggested that multiple temporal processes may operate. Third, there were consistent individual differences in task-induced workload responses. Implications of the findings for evaluating NPP interface designs and monitoring operators are discussed.

1. Introduction

The operation of nuclear power plants (NPPs) raises a variety of human factors issues, including potential loss of vigilance and alertness. A primary function of the human NPP reactor operator (RO) is monitoring the state of the plant to determine whether it is operating correctly. Operators routinely monitor an array of control panels and computer displays, to detect system parameters that may deviate from normal operational states (O'Hara and Higgins, 2010; O'Hara et al., 2008). Recent literature has identified a vigilance aspect of detection tasks (Reinerman-Jones et al., 2013). Vigilance is traditionally defined as the operator's ability to maintain the focus of attention and to remain alert to stimuli over prolonged periods of time (Warm et al., 2008). Loss of vigilance may be expressed in failures to detect critical stimuli or 'signals', for example, a gauge indicating that steam pressure exceeds an acceptable value. Often, vigilance deteriorates over time ('vigilance decrement': Warm et al., 2008), leading to an increased error rate in signal detection. In the context of NPPs, vigilance is renamed 'detection' and is operationally defined as continuous monitoring of a control parameter for identification of changes (Reinerman-Jones et al., 2013). The present study investigated operators' vulnerability to vigilance decrement over short time durations when performing a detection task, using multiple metrics.

1.1. Vigilance in the control room

Vigilance decrement is readily demonstrated using laboratory signal detection tasks (See et al., 1995), and field studies in industrial, military, transportation and medical contexts (Warm et al., 2008). Vigilance may be important for NPP operation (Laughery et al., 2002; Mumaw et al., 2000; Thornburg et al., 2012), but controlled empirical studies of the issue are lacking. The applied relevance of laboratory studies of vigilance remains controversial, in part because of the much greater complexity of real systems and displays (Donald, 2008). On the basis of field observations, Mumaw et al. (2000, pp. 42–42) concluded that "monitoring during normal operations was a complex, cognitively demanding task that was better characterized as active problem solving than as passive vigilance." Specifically, these authors determined that effective monitoring, or what recent literature calls detection, depended on understanding the current status of plant, which defined which signals were critical at any given time. Operators also devised a wide range of strategies to ease detection demands, such as manipulating alarm set points and leaving sticky notes to flag unusual indicators. Mumaw et al. (2000) also drew attention

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to differences in routine detection, for example during equipment testing, and monitoring alarm signals, which are typically salient.

Mumaw et al.'s (2000) analysis indicates the dangers of naïve generalization from laboratory findings. At the same time, several recent research advances suggest the potential relevance of vigilance to the NPP domain. First, much basic and applied research can be accommodated within a common workload-resource model (Hancock, 2013; Warm et al., 2008). Although vigilance assignments appear superficially undemanding, they often impose high workloads that over time induce cognitive fatigue and increased vulnerability to error in signal detection. That is, vigilance is not necessarily a 'passive' task, but one that depends on active, effortful interrogation of task stimuli. Workload is a known issue for the NPP operator (Hwang et al., 2008; Lin et al., 2011), and its impact may extend to the detection task performed by the operator (Ha and Seong, 2010). Second, when task workload is high, vigilance decrement may be observed even on tasks of short duration (Matthews et al., 1990; Temple et al., 2000). Brain metabolic activity during certain vigilance tasks declines over periods as short as a few minutes (Warm et al., 2012). Third, due to high workload and limited personal control of the task, vigilance tasks are often stressful (Hancock, 2013; Warm et al., 2008). Similar stress factors appear to predict operator performance in both laboratory and real-world settings (Matthews et al., 2013). Fourth, as in other human factors domains, the increasing automation of NPPs is changing the role of the RO from an active controller of the system to a more remote monitor of automated systems (Jou et al., 2009; Lin et al., 2010). The changing role of the RO is likely to produce greater vulnerability to loss of vigilance.

1.2. Multivariate assessment of mental workload and stress

Valid assessment of mental workload is operationally important, although multiple metrics are necessary to evaluate workload and stress (Matthews et al., 2015, 2002; Taylor et al., 2010). Mental workload is typically defined as the total demand for limited cognitive resources imposed by the tasks performed by the operator (Wickens et al., 2013). Subjective measures such as the NASA Task Load Index (NASA-TLX: Hart and Staveland, 1988) are commonly used for assessment. The validity of the NASA-TLX is well-established (Vidulich and Tsang, 2012) and it is sensitive to task load variation in NPPs (Gao et al., 2013; Hwang et al., 2008; Lin et al., 2011). However, subjective scales are prone to the biases of self-report, suggesting a need for objective indicators. Typically, performance levels decline with increasing workload, but performance and workload changes may dissociate (Horrey et al., 2009).

Psychophysiological measures also provide objective workload metrics. Simulation studies (Gao et al., 2013; Hwang et al., 2008) have shown that electrocardiographic (ECG) and ocular indices are sensitive to manipulations of task complexity. Studies from other process control environments (e.g., Hockey et al., 2009) suggest that electroencephalographic (EEG) measures such as frontal theta also reflect operator workload. Slow-wave EEG activity has been linked specifically to vigilance decrement (Kamzanova et al., 2014). ECG and EEG metrics may be supplemented by hemodynamic measures of metabolic activity in brain areas supporting attention (Warm et al., 2012). Loss of vigilance is frequently accompanied by declining cerebral bloodflow velocity (CBFV), measured using transcranial Doppler sonography (TCD: Warm et al., 2012). Another hemodynamic index linked to mental workload is level of blood oxygenation in frontal areas measured by functional near infrared (fNIR) spectroscopy (Ayaz et al., 2012).

However, few studies have compared these various workload metrics for their sensitivity and diagnosticity, and psychometric evidence suggests that they may be only weakly inter-related (Matthews et al., 2015). Multivariate assessment of workload may be necessary to evaluate the demands of different elements of the NPP operator's task (Hwang et al., 2008). In addition, continuous psychophysiological recording of the operator may be diagnostic of loss of alertness (Matthews et al., 2010; Reinerman-Jones et al., 2011). Diagnostic monitoring may identify ROs who are failing to sustain attention effectively, and in need of support from other team members or technological aids.

1.3. Aims and hypotheses

The current study used a simulation of NPP operations performed by a RO and Senior Reactor Operator (SRO) working as a team (Reinerman-Jones et al., 2013). The simulation is designed to support the primary tasks of operators identified by O'Hara et al. (2008): monitoring and detection, situational assessment, response planning, and response implementation. It also supports a further key task, checking an instrument or control to verify that it is in the appropriate state (Reinerman-Jones et al., 2013). The SRO initiated the tasks via three-way communication. For example, prior to each task the SRO initiates an instruction to the RO, the RO signals understanding of the instruction, and the SRO confirms the comprehension statement. At this point, the RO performs the task in the simulator. The present study aimed to compare workload responses to a detection task with responses to two routine task elements, checking a single control, and implementing a single response (opening or closing a switch). Specific issues addressed were as follows:

Workload profiles of tasks. We aimed to assess EEG, ECG and hemodynamic responses to detection, checking and response implementation tasks, along with subjective stress and workload. Given that even short-duration detection tasks impose high mental demands (Warm et al., 2008), we hypothesized that the detection task would show the highest level of workload, shown in both objective indices such as decreased heart rate variability (HRV: Hwang et al., 2008), EEG frontal theta (Gevins and Smith, 2003) and increased frontal blood oxygenation (Warm et al., 2012). We also hypothesized that detection would elicit stress, as indexed by the key factors for subjective stress: distress, worry and loss of task engagement (Matthews et al., 2002, 2013). In naturalistic settings, tasks include both communication and task execution. Detection, however, may involve periods during which the task is executed without communication. To test the hypotheses, we performed both a 'naturalistic' comparison of the three tasks, including communication and execution, and a more restricted comparison of the execution phase of the detection task only with the other two. (It was not possible to separate communication and execution phases of the relatively short checking and response implementation tasks.)

Vigilance during detection. We tested for changes in neurocognitive indices of alertness in a sequence of five-minute intervals, during which the detection task was executed. It was hypothesized that performance would decline over time, along with changes in neurocognitive indices diagnostic of loss of alertness, especially increased slow-wave EEG activity and decreased CBFV (Kamzanova et al., 2014; Warm et al., 2012).

Predictors of neurocognitive functioning during detection. We tested whether indices of operator alertness during execution of the detection task could be predicted from indices secured from the relatively unchallenging checking and response implementation tasks. It was hypothesized that indices of response to these tasks would be more predictive than baseline measures, given that task-induced workload responses show inter-individual consistency across different levels of task demand (Matthews et al., 2015).