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Navigating Fine Line Between Operational Effectiveness And Mental Overload In Control Room Operations

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In control room settings, especially within the chemical industry, the cognitive state of operators is critical. The key challenge is maintaining vigilance without causing mental overload. With the escalating complexity of control systems, the likelihood of mental overload and diminished Situation Awareness grows, a situation further aggravated by alarm floods. Such events, constituted by multiple concurrent alarms, risk critical warning omissions or delayed responses, pushing operators towards their boundary of cognitive limits. This boundary between vigilance and overload is not only a matter of operational efficiency but an anchor point of safety and reliability in process control industries. Thus, investigating the impact of various alarm scenarios on operators is imperative.

This study seeks to deepen our understanding how varying complexities and support levels of alarm scenarios impact control room operators' Mental Workload (MWL), Situation Awareness (SA), and performance. Utilising a simulator of a chemical plant's control room environment, we aim to understand operators' responses to highly complex situations through a comprehensive methodological approach, including subjective assessments (NASA-TLX questionnaire) and objective measures (SPAM method and performance metrics).

In addition, we explore Adaptive Automation (AA), tuned on the operators' cognitive state, as a potential solution against overload, and consequently sustaining peak performance and safety.

This study is a part of the *Collaborative Intelligence for Safety-Critical Systems* project, and the data has been collected in two institutions, TU of Dublin and PoliTo university, under the Live Lab 3 collaboration.

Utilizing a simulated control room in a formaldehyde production plant (Demichela et al., 2017), the study examines operator response to simulated component failures that trigger both visual and auditory alarms. The conditions for the experiment make it an ecologically valid representation of a control room, but also with the necessary simplifications to make it suitable for people without experience in the chemical industry.

Experiment participants were sorted into four groups, each receiving different levels of alarm management support, to assess the impact of different support tools on operator performance and cognitive load. Throughout scenarios, each lasting 15-20 minutes, participants addressed malfunctions of increasing complexity, and were tested on their ability to identify and respond to significant alarms, guided by a procedure manual with specific monitoring and actions protocol. The first two scenarios involved handling pressure drops in the methanol tank presenting two alarms—one of which was critical. In contrast, the third scenario escalated to a plant-wide cooling system failure, leading to overheating, and triggering an alarm flood with multiple critical alarms. Further details can be found in (Amazu et al., 2023).

Data was collected from 140 participants—92 in PoliTo and 48 in TU Dublin, with an average age of 26. Many of the participants are students from Chemistry Engineering, with allows to compare performance along different levels of familiarity with the Chemical Industry. The collected data from the experiment pertinent to this study is mapped in Table 1.

Table 1. Data Collection Sources and Metrics for Assessing Performance Aspects in this study.

Data source	Description	Performance aspect	Type	Metrics	References
Simulator logs	Records participants' interactions with the simulator, capturing their responses to critical alarms and their corrective actions.	Task Performance	Task-Performance	- Response and completion times - Number of Actions - Error Rate	(Xu et al., 2018)
Demographic information survey	Gathers basic demographic profiles and operational familiarity of participants. for context analysis	-	Self-reporting	- Age distribution - Control room Familiarity - Chemical industry Familiarity - Background	(Zarei et al., 2016)
Situation Presence Assessment Method (SPAM)	Evaluates participants' SA by querying their understanding of critical alarms, underlying causes, and the implications of corrective actions.	Situation Awareness	Observer Rating	Correctness of the answer on the 3 SA levels (Perception, Comprehension and Projection)	(Durso et al., 1995)
NASA-TLX	Standardized questionnaire to evaluate the perceived workload and stress levels experienced by participants during tasks.	Workload	Self-reporting	- Mental Demand - Physical Demand - Temporal Demand - Performance - Effort - Emotional Stress	(Heart et al., 1988)
Situation Awareness Rating Technique (SART)	Enables operators to rate system design on bipolar scales, assessing perceived situational awareness on 7-point scales.	Situation Awareness	Self-reporting	- Demand - Supply - Understanding	(Taylor, 1995)
Support system evaluation	Evaluates support effectiveness through user ratings on alarm clarity, priority differentiation, and procedural guidance.	Plant Performance	Self-reporting	- Alarm list support - Alarm priority support - Procedure support - AI support	(Sulaiman & Hasbullah, 2009)
EEG	Captures participants' brain wave patterns to assess mental workload and vigilance.	Workload	Physiological	- Task Load Index - Engagement Index	(Kamzanova et al., 2014)

Data Analysis approach

The performance data from the Simulator logs and surveys responses were processed and compared statistically for different groups and scenarios and correlated with the performance data. In addition, EEG data was processed by artifact removal and computing relevant vigilance indices (Kamzanova et al., 2014), which were then correlated with participant and task variables. Findings from this analysis will be presented on site at the ESREL 2024 conference. The results will show how the cognitive state of operators is affected by alarm floods, and how different approaches to provide support alter it. Moreover, they aim to lead a discussion about Adaptive Automation, and how it can be modulated according to levels of MWL and SA to provide support in critical moments.

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