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Multifactorial Measurement of Mental Strain for Developing Adaptive Assistance Systems in Control Rooms

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ABSTRACT

This study investigates the mental strain among control room workers, as a requisite for developing adaptive assistance systems, specifically for the energy sector. Through preliminary interviews with personnel of a German energy supply company, we identified mental workload, attention, emotional states, and mental fatigue as relevant user states. Twenty male dispatchers from the same company participated in the study, completing validated questionnaires including the Workload Profile, Activation-Deactivation Adjective Check List, Flow-Experience Questionnaire, and Self-Assessment Manikin during normal shifts. Results revealed moderate workload demands with high variability, stable tension and activation levels, moderate concentration, and positive emotional states during shifts. These findings provide valuable insights for designing adaptive assistance systems that can respond dynamically to operators' needs, potentially enhancing job satisfaction, performance and efficiency in control room settings.

Keywords: Mental stress, Mental strain, User states, Human-computer interaction

INTRODUCTION

The energy supply sector faces growing workplace challenges, especially in Germany, where employees report high stress levels (Federal Institute for Occupational Safety and Health, 2024). Control room operators, who are responsible for overseeing and managing critical processes in power generation and distribution, are particularly vulnerable due to the multitasking and decision-making they are required to perform under pressure (Jeschke and Lafrenz, 2015; Schwarz et al., 2010). Moreover, they respond to alarms and address disruptions, from technical malfunctions to external threats, e.g., extreme weather or cyberattacks, any of which could result in cascading system failures (Petermann et al., 2010). All these complex situations led to increased operators' mental strain, which highlights the need for better support systems for decentralized power grids (Afzal et al., 2022).

Given the increasing cognitive demands on control room operators, human-computer interaction strategies, such as *adaptive assistance systems* (AAS), have become essential for mitigating mental strain (Witte et al., 2020). Germany's Federal Institute for Occupational Safety and Health

(2015) defines AAS as "methods, concepts and computer-aided work systems that support work activities in a context-dependent and, to some extent, even independent manner". Unlike adaptable systems, which allow users to customize settings, adaptive ones automatically adjust to users and their environment (Buchholz and Kopp, 2023), helping prevent cognitive overload by providing tailored guidance during critical operations. While standards like ISO 9241–210 (2010) guide user-centered human-system interaction design, an additional key factor in developing effective AAS is understanding user states – a multidimensional construct including stress, fatigue, motivation, attention, situational awareness, and emotional state (Schwarz et al., 2014). Research suggests that monitoring user states in real time allows systems to adapt dynamically to an operator's needs, optimizing workload distribution and reducing excessive mental strain (Fuchs et al., 2020; Schwarz and Fuchs, 2018).

In response to these challenges, the project "Optimized Work Design for Network Control Rooms of Critical Infrastructure" was launch in 2022. Funded by the German Federal Ministry of Education and Research (BMBF), the project seeks to optimize (mental) stress in control rooms by developing adaptive assistance systems and simulators in the electricity and gas industry (Federal Institute for Occupational Safety and Health, 2022). A key prerequisite for improving mental strain in these activities is knowing which cognitive facets contribute to overall workload and how this fluctuates over time during work. This requires the establishment of a reliable but practicable measurement method for the various facets. To this end, this study investigates baseline operator states during routine conditions as a foundation for the development of those adaptive assistance systems.

Operators in a gas and energy control center participated in data collection over a series of normal shifts. Multiple data gathering was employed, including physiological monitoring, environmental data, and self-assessment questionnaires. This manuscript focuses only on the results related to the subjective assessment of mental strain. Drawing on early-stage interviews with control room personnel, we identified mental workload, attention, emotional states, and mental fatigue as the relevant user states. Based on these findings, the Workload Profile (WP) (Tsang and Velazquez, 1996), the Activation-Deactivation Adjective Check List (AD-ACL) (Thayer, 1986), the Flow-Experience Questionnaire (Bartzik et al., 2021a), and the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994) were selected. Therefore, the aim of this paper is to present the results of the subjective assessment of user states within an energy sector control room in Germany.

METHODOLOGY

Participants

Participants were dispatchers employed at an energy supply company in Germany. Recruitment was conducted through corporate channels, with study information disseminated via official email communication. Initially, 30 potential participants expressed interest in the study (22 from the electricity division and 8 from the gas division). Individual appointments were subsequently scheduled. However, 10 participants withdrew from the study due to operational constraints and scheduling conflicts. At the end, 20 dispatchers participated in the study. Upon arrival, they provided written informed consent. This study was approved by the ethics committee of Fraunhofer Institute for Communication, Information Processing and Ergonomics (No. 24_004).

Materials

We quantified mental workload with the Workload Profile (WP) (Tsang and Velazquez, 1996), which offers superior sensitivity in distinguishing between task demands (Barajas-Bustillos et al., 2023; Rubio et al., 2004). Base on Wickens' (1992; 2008) Multiple Resource Theory, the WP postulates that multiple cognitive resources are available for processing mental workload. For this study, the WP was translated into German and the original scale was adapted from 0–1 to a percentage of 0–100 to improve interpretability. The German version of the WP was subsequently validated in multitasking scenarios (Rey-Becerra et al., 2025) and showed high internal consistency (Cronbach's α > .88). We calculated the mean percentage for each resource.

Attention was assessed using the Flow Experience Questionnaire (Bartzik et al., 2021a), as flow reflects an optimal state of focused attention where cognitive resources are fully aligned with the task, resulting in deep concentration and peak performance (Csikszentmihalyi, 1975; Peifer, 2017). This instrument is available in German (Bartzik et al., 2021b), and we used the frequency scale ranging from 1 (never) to 6 (always). We calculated the average flow score using the first nine items.

We used the Activation-Deactivation Adjective Check List (AD-ACL) (Thayer, 1986) to assessed mental fatigue, a state between wakefulness and tiredness (Hamann and Carstengerdes, 2020). We modified some items of a previous German version (Imhof, 1998), changed the original scale into a Likert-type scale ranging from 1 (not at all) to 5 (completely) and validated in the same multitasking study mentioned before (Rey-Becerra et al., 2025), showing high internal consistency (Cronbach's α > .88). The two-dimensional structure, representing energetic arousal (activation) and tense arousal (tension), was confirmed. Accordingly, we calculated average scores for each dimension.

Finally, we measured emotional states with the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994), available in German (Fischer et al., 2002), which evaluates valence, arousal, and dominance on a nine-point pictorial scale. We found that emotions characterized by negative valence (pleasant vs. unpleasant) and high arousal (activated vs. deactivated), such as frustration and fear, may limit attention and impair information processing (Staal, 2004). Therefore, we computed the mean score for each emotional dimension.

Procedure

The study was conducted on-site at the company's facilities. Participants arrived at a designated room prior to the start of their shifts. Upon arrival, they were given a tablet to complete questionnaires for subjective measures. In addition, participants were provided with a sensor-integrated shirt and eye-tracking glasses for objective physiological data collection. The experimenter provided detailed instructions on the protocol. Each participant generated a unique code to facilitate integration of questionnaire responses with physiological data. Demographic questions and the AD-ACL were administered at the beginning of the shift. Participants then proceeded to their regular workstation to perform their standard operational duties. Following the shift, participants returned to the room and completed the WP, the Flow, the SAM, and the AD-ACL once again. Upon completion, all monitoring devices were removed and the experimenter performed a brief interview regarding their experience with the measurement devices and tablet interface.

The data were subsequently downloaded from the tablets in.csv format. These files were processed and the data were subsequently transformed and analyzed using RStudio (v4.2.3; R Core Team, 2023). Descriptive statistics and correlation matrices were computed with the psych package (v2.2.5; Revelle, 2024) to examine the expected relationships between all constructs. Following Cohen's (2013) guidelines, correlation coefficients were interpreted as small (0.1), moderate (0.3), or large (0.5). We retained outliers in the analysis, as they represented genuine extreme values (Burke, 1998). We conducted repeated-measures analysis of variance (ANOVA) using the stats package (v4.2.3; R Core Team, 2023) to explore the effects on user states. All statistical requirements were verified, with a significance level set at $p < .05$.

RESULTS

A total of 20 dispatchers participated in the study, only one dispatcher was from the gas division. All participants were men with an average age of 35.8 years (SD = 7.8) and work experience of 11.3 years (SD = 5.6). Three of them participated more than once, which makes a total of 24 measurements. However, we had to delete one measurement because the data on the tablet was incomplete. Of the remaining 23, we had 18 in the early shift and 5 in the late shift. Table 1 (next page) shows the mean and standard deviation of the user states evaluated. We found no statistical difference between shifts for any of the variables. Nor was there any difference between before and after the shift in energetic arousal or in tension arousal.

In addition, we estimated Pearson correlation coefficients among the user states variables. Most relevant correlations revealed several significant relationships among them. Post-shift energetic arousal was positively correlated with flow experience ($r = .69$, $R^2 = .47$, $p < .001$). Post-shift tension was positively correlated with central mental processing ($r = .44$, $R^2 = .20$, $p = .03$), auditory modality ($r = .53$, $R^2 = .28$, $p = .01$), manual reaction ($r = .50$, $R^2 = .25$, $p = .02$), and verbal reaction ($r = .42$, $R^2 = .18$, $p = .04$). Arousal levels correlated significantly with all Workload Profile resources ($r > .42$) except the spatial dimension and were positively associated with tension arousal before ($r = .67$, $R^2 = .45$, $p < .001$) and after shifts ($r = .57$, $R^2 = .32$, $p < .001$). A negative correlation was found between arousal and energetic arousal before shifts ($r = -.50$, $R^2 = .25$, $p = .02$).

Valence levels showed moderate positive correlations with flow experience ($r = .54$, $R^2 = .29$, $p < .01$) and post-shift energetic arousal ($r = .53$, $R^2 = .28$, $p = .01$).

Table 1: Descriptive statistics for the whole sample and per shift – mean (SD).

Questionnaire	Dimension	All (n = 23)	Early Shift (n = 18)	Late Shift (n = 5)
Workload Profile	Central	59.2 (30.3)	58.7 (29.2)	61 (37.8)
	Response	53.7 (33.9)	54.8 (33.3)	49.8 (39.7)
	Spatial	35.9 (36.9)	37.1 (37.3)	31.8 (39.2)
	Verbal	63.3 (32.0)	63.1 (31.4)	64.0 (37.8)
	Visual	60.3 (34.0)	59.3 (34.0)	64.0 (37.8)
	Auditory	45.9 (35.4)	45.8 (34.9)	46.0 (41.6)
	Manual	48.2 (33.6)	51.0 (33.1)	38.0 (37.0)
	Speech	61.2 (32.2)	62.7 (28.4)	55.8 (47.0)
AD-ACL	Energetic arousal (before)	3.5 (0.7)	3.6 (0.6)	3.3 (0.9)
	Energetic arousal (after)	3.4 (0.9)	3.4 (0.8)	3.2 (1.1)
	Tension arousal (before)	1.9 (0.7)	1.9 (0.7)	2.1 (0.4)
	Tension arousal (after)	2.0 (0.7)	2.0 (0.7)	1.9 (0.4)
Flow Experience	Flow	3.8 (0.7)	3.8 (0.6)	4.0 (1.0)
SAM	Valence	6.8 (1.1)	7.0 (0.8)	6.0 (1.7)
	Arousal	3.4 (1.3)	3.4 (1.3)	3.6 (1.5)
	Dominance	4.0 (1.3)	4.0 (1.3)	3.8 (1.3)

DISCUSSION

The aim of this manuscript was to present the results of the subjective assessment of mental strain in control rooms. We focused on key user states, such as mental workload, attention, emotional states, and mental fatigue, identified through interviews with dispatchers. We used validated questionnaires (WP, AD-ACL, Flow-Experience, and SAM) to assess these states. Data were collected from 20 dispatchers (23 measurements) at a German energy supply company. Notably, no critical incidents (e.g., blackouts) occurred during the study period, only occasional interruptions.

On average, the WP indicated a moderate overall demand but with a high variability, which might reflect individual differences among dispatchers. From all resources, "spatial" were the least used, likely due to the static nature of the workstations. Dispatchers showed moderate energetic arousal and low-tension arousal, both before and after shifts, reflecting that they were slightly activated but overall relax during the shift. Flow experience was moderate, indicating that they were relatively busy and focused during their shifts. Notably, post-shift energetic arousal correlates with flow, while post-shift tension arousal was linked to increased use of auditory, manual, and vocal resources. This suggests that higher levels of concentration lead to greater activation after the shift, and higher levels of strain lead to greater use of these resources, possibly reflecting heightened cognitive demands. These findings resonate with Afzal et al. (2022), who emphasize that variability in cognitive demand is inherent to control room work, driven by dynamic coordination and task complexity.

Emotional state assessments revealed positive emotions (high valence), with a relatively relaxed state (arousal) and moderate control over tasks (dominance). Interestingly, higher arousal was associated with greater cognitive demand, except in the spatial domain, which had the lowest demand. Besides, low tension and high activation before the shift are related to low arousal during the shift, suggesting effective emotional regulation and a reduction in strain. Finally, positive emotions during the shift were linked to deeper flow during the shift and increased energy arousal after the shift, highlighting the value of fostering positive affect to enhance concentration and activation. These findings align with Osvalder et al. (2015), who also found that operators in well-designed control rooms reported positive emotions, highlighting the importance of ergonomic and environmental factors for well-being and performance.

Based on our findings, we propose a typical dispatcher profile as baseline, assuming that both shifts experience similar levels of stress. In general, dispatchers maintain stable stress levels during their shifts and experience moderate concentration levels, meaning they are engaged and focused, but not overwhelmed. Their activation levels remain steady, while tension levels are low, contributing to a generally positive and calm working mood with a moderate sense of control. Moreover, they experience positive emotions during the shift which promote greater concentration and energy post-shift. These findings suggest that dispatchers experience their work as positive, particularly when high-stress situations are infrequent.

From a practical standpoint, these results are valuable for designing AAS in control rooms. In our case dispatchers were not overwhelmed, introducing more variety or responsibility into their roles could enhance engagement and further optimize performance. However, if control over tasks diminishes, interventions such as additional training or support systems may be needed to maintain their sense of control. Moreover, because arousal, activation, and flow are closely linked, creating a supportive work environment could not only increase job satisfaction but also improve overall efficiency. In line with a human-centered approach, AAS should adapt not only to task complexity but also to users' states to preserve their autonomy and promote confidence (Buchholz and Kopp, 2023).

Our study highlights the value of a multifactorial approach to measuring mental strain, which can guide the development of AAS that adapt to the changing needs of dispatchers in control room settings. While primarily focused on the energy sector, these findings are also applicable to other high-stakes domains like traffic monitoring or emergency supervision (Pohl et al., 2018, Weißenböck et al., 2017), where operators face similar cognitive demands. One of the key limitations of this study was the limited participation of the dispatchers, which may have hidden potential differences between shifts. Despite this, the use of real dispatchers in an operational setting provides meaningful insights into mental strain in practice. Future studies will be conducted to assess the effectiveness of AAS while taking users' states into account

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