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ORIGINAL ARTICLE

Impact of workload on cognitive performance of control room operators

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Abstract

Workload has long been considered as one of the important factors for personal functions and malfunctions, particularly in complex systems. Undertaking operations in workstations of such systems usually entails complex tasks and poor cognitive performance of their operators may contribute to human error and critical subsequent consequences. Although many studies have investigated the effects of workload on the cognitive performance, there is a gap for specific jobs and operations such as control room operation. This paper then aims to determine that what dimensions of the workload has more impact on cognitive performance of a combined cycle power plant (CCPP) Control room operators. Control room operators from two CCPPs participated ($n = 95$) in this study. Hierarchical task analysis (HTA) was employed to perform the job analysis. To assess the perceived workload, NASA Task Load Index (NASA-TLX) was performed at the end of the work shift. The participants were subjected to three cognitive performance tests including sustained attention, simple reaction and working memory at the beginning and end of the work shift. The values of mental demand on check and control tasks (92.17 ± 4.38), decisions about abnormal conditions (90.16 ± 5.71) and reporting (85.09 ± 3.25) were high. The task of communication and coordination in terms of temporal demand (71.66 ± 7.3) and performance (68.04 ± 4.92) had higher values compared to other tasks. The highest weighted workload (84.27 ± 6.48) was also attributed to the task of checking and controlling. Sustained attention and working memory were more susceptible to excessive workload among CCPP control room operators.

Keywords Workload · Cognitive performance · Task analysis · Power plant control room

1 Introduction

The advent of enhanced automation in the process industries together with increasing the system complexity have already created a large number of tasks particularly based on supervising and diagnosing activities. It is, therefore, evident that if such activities are performed incorrectly, serious unpredictable failures as well as opportunities for whole system malfunctions might occur (Hollnagel and Woods 2005; Seife 1999).

Workload is usually defined as the amount of mental effort or information that an individual can put in or process at a certain time to complete a task (Fernandes and Braarud 2015; Miller 1953). It is a multidisciplinary concept (Young and Stanton 2004) and has long been recognized as a major factor in evaluating human performance mainly through objectively assessing the completion of several specific observable tasks (Eggemeier and Wilson 1991; Parasuraman et al. 2008).

It should also be noted that the concept of workload mainly includes the mental and physical dimensions such as mental and physical demand, frustration, performance and temporal demand which are always interconnected and when one is performing a particular task, the physical and mental dimensions of the workload cannot be completely separated (Fernandes and Braarud 2015; Meijman et al. 1992).

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On the other hand, evaluation of an occupational task commonly requires a thorough assessment of the Mental Workload (MWL); since human errors and delayed information processing have been cited as the major consequences of excessive levels of MWL (DiDomenico and Nussbaum 2011; Ryu and Myung 2005).

Previous studies such as the one by Yang et al. revealed that multiple psychological and physical factors affect peoples' perceptual and concentration capacities and may induce human error. Some of these factors include physical and mental stress, job fatigue, inappropriate employee relationships, and overload of information processing (Yang et al. 2012).

Prolonged inactivity of the control room operators as well as overloading them with manual command structure may contribute to several problems as well (Vanderhaegen 1997).

In such circumstances, the mental workload surpasses processing capacity, and the operator might delay in processing information, which might eventually result in human error or related events (Yang et al. 2012).

Researchers have suggested the optimization of workload allocation to individuals to reduce human error, improve system safety, and improve their productivity and satisfaction (Ha et al. 2007).Conversely, some authors believe that both low and high MWL might affect the individual's normal performance as well (Lin et al. 2011). Excessive levels of MWL is considered as a key contributor to emotional stress, depression or burnout (Cinaz et al. 2013) and decline in critical decision-making processes (Hannula et al. 2008). Therefore, accurate assessment and prediction of the MWL levels are logically necessary.

In general, there are three sets of methods for evaluating MWL: subjective methods, performance-based methods, and methods based on psycho-physiological measurements (Dey and Mann 2010; Di Stasi et al. 2009; Hwang et al. 2008; Jo et al. 2012; Rubio et al. 2004). Subjective methods provide us with information about the user's sense toward the task conditions (Hockey 1997). In this regard, the NASA-TLX load index assessment method (Hart and Staveland 1988) has been one of the most widely subjective methods used for evaluating physical and mental demands (Braarud 2020; Fernandes and Braarud 2015).

Human cognition is considered as a set of information-processing activities which take place inside the mind and could be studied by carefully observing the performance in well-defined situations (Hollnagel and Woods 2005).

Our cognitive performance might commonly include several mental processes such as attention, perception, activity of memory, decision-making, problem-solving, and reaction time (RT) (Monteiro et al. 2018), among which, our attention facilitates the process of taking information and enables sustained performance on tasks over extended periods of time (Yiend 2010).

Human working memory processes which normally handle the necessary information for complex cognitive tasks such as learning and reasoning, has shown to have a limited capacity with a temporary capability; particularly for storing information (Naserpour et al. 2014; Yiend 2010). Increase in the capacity of the working memory would enhance the levels of attention and results in protection against distractions (Golmohammadi et al. 2020; Simon et al. 2016).

According to the previous studies, to understand the human behavior in complex systems, it is crucial to study the cognitive aspects of human behavior through testing and enhancement of performance measures (Bullemer and Nimmo 1994; Fernandes and Braarud 2015; Manca et al. 2013). Accordingly, several methodologies have been proposed to integrate different cognitive dimensions of human error (Mosleh and Chang 2004; Pate-Cornell and Murphy 1996).

The effect of workload on operator performance is one of the most widely studied aspects of human empowerment (Bowers et al. 1997). It is now well established that several circumstances in process industries such as emergency situations and process transitions (start-up, shut-down, grade changes, etc.) often cannot be automatically controlled and require active human intervention (Dai et al. 2016; Seng and Srinivasan 2004; Williams 2014; Zhang and Zhao 2017). Therefore, in such circumstances, it is likely that the operator has to bring the process back to normal operating conditions using his/her mental process model (developed partly based on training), prior knowledge and experience. Should there exists a mismatch or inconsistency between the operator's expectations of the process conditions and their mental processing, human errors occurs. It is believed that operator's mental modes which are mainly categorized as skill-based, rule-based, and knowledge-based (Rasmussen 1982) have a major impact on the way they usually deal with emergency situations.

Operators turn to a skill-based mode when performing repetitive tasks, not requiring mental effort. In this process, they use a law-based model for dealing with emergencies, particularly in the fully familiar process to the operator. On the other hand, when the operators face a new situation, they rather use knowledge-based models while law-based or skill-based models are not accessible. This is where they are obligated to use their knowledge for the identification of the appropriate actions (Seng and Srinivasan 2004).

The power plant control room is similar to the brain in the human body; a unit which manages and monitors the overall processes of safe power generation (Prostejovsky et al. 2019).

The operators of such control rooms have, therefore, the key roles in the process of generating electricity as well (Hugo et al. 2018). The concept of human performance as well as its evaluation in a power plant control room is a principal aspect and is generally based on the accurate and efficient accomplishment of a task according to predefined parameters. Power plant control room activities are commonly organised in shifts; normally including 24 h. During the work shifts, control room operators almost always have to maintain a high level of vigilance and full attention (Corradini and Cacciari 2002).

As operators often must process large amount of information when they are dealing with an emergency situation, the likelihood of taking suboptimal decisions or committing an error would become immoderate. They are, therefore, likely to experience excessive cognitive workload during these situations (Bhavsar et al. 2017) which in turn contribute to their unacceptable and poor performance (Heard et al. 2018). It is then necessary to be able to measure the cognitive functions of operators based on their mental resources or memory capacity as well as job/task demands (Hart and Staveland 1988). Moreover, the cognitive workload of a task is a function of the relationship between operators' working memory demand and cognitive capacity (Mayer and Moreno 2003) and any discrepancy between these two would lead to committing a human error.

Regarding the above considerations, however, it is reasonable to consider the fact that the study of the control room operators is the study of their internal functions, either as information processing or as cognition (Hollnagel and Woods 2005). So that, evaluating the MWL and its relationship with cognitive performances prevailing among control room operators of power plants not only would enhance the operators' performance, but also improves the occupational health safety conditions of these plants (Jazani et al. 2016).

Given the need for attention and focus on the human–machine relationship as well as precise and timely response to the adjustment of process and processing systems, and the fact that the tasks of operators, require numerous cognitive performances such as continuous attention and being accurate, ability to detect and visualize, ability to use memory efficiently along with planning and decision-making; identification, prediction and control of the workload, the cognitive performance of the control room operator is necessary to ensure the stability of the power grid along with improving the comfort, efficiency, and safety in the workplace.

1.1 Literature

The impacts of workload on operators' performance have been extensively investigated by previous researchers (Bowers et al. 1992; Lin et al. 2011). In the overview on the conducted studies, there has been a great deal of concentration on the management of the mental workload level during performing a task, particularly with regard to the workload in the grueling and complicated tasks such as air traffic control safety (Argyle et al. 2020; Edwards et al. 2017).

MWL is also an integral subject of the concern in complicated systems such as control rooms of Nuclear Power Plants (Ha et al. 2007; O'Donnell and Eggemeier 1986; Xie and Salvendy 2000); mainly due to the workload impact on error-making and the human performance (Lin et al. 2011).

The study conducted by Heart and Starland indicated that NASA-TLX provides the total workload due to discriminating between the tasks on the one hand and the cognitive and physical requirements on the other hand (Hart and Staveland 1988). They also acknowledged that the determined weight and dimensions for each aspect of NASA-TLX provide vital diagnostic information with regard to the resources creating workload in the tasks. In another study, Vidulich and Pandit (1987) reported three meaningful correlations between NASA-TLX and personality tests (Gawron 2019).

Workload, situation awareness, and individual performance were investigated in control rooms, and a similar pattern and situation awareness were indicated through the assessments. The authors of this work noticed a meaningful correlation between the workload and individuals' performance, in a sense that decreasing the workload improves their performance (Fernandes and Braarud 2015).

Several researchers who had investigated the workload in the control room tasks automation designing process concluded that there is the greatest extent of workload and human error in manual operations (non-automatic). Such an issue was subject to the physical requirement factor. In semi-automatic operations, the individuals had a great deal of frustration. Moreover, the time of manual and semi-automatic operations had a close correlation with the mental demand as well (Jou et al. 2009).

In the study by Reinerman et al. the workload was investigated using three mental, operational, and physiological methods in the control room. The participants had a greater workload in the identification task realm, not to mention that the mental demand was higher in those tasks. Meanwhile, according to NASA-TLX, the frustration scale and the total workload was at the highest point (Reinerman-Jones et al. 2015).

The simultaneous effect of metabolic stressors, eating breakfast and sensory stressors (such as being exposed to the noisy environments) on the cognitive performance was also measured and the results indicated that the interactions between the two stressor agents have no impact on cognitive performance; seemingly that abrupt noise bursts leads to stimulation, thus, increasing attention (Bottenheft et al. 2020).

One of the reasons the cognitive performance measurement is carried out is that there are some issues such as a decline in efficiency and an increase in risks, errors, and incidents, all of which occur if the cognitive performance is not appropriate. In fact, the operators' awareness about the loss of their proficiency may lead to mental pressure, whose consequences are of significant importance in terms of the safety of critical tasks (Sinclair et al. 2012).

In case of any attention level disturbance, unsafe acts may occur. Comprehension level is reduced for a few reasons, including high workload or stress, panic, lack of attention, and education failure or poor conditions (Hollnagel 1998; Kubota et al. 2001; Samima et al. 2019; Vanderhaegen 1999b; Vanderhaegen et al. 2020).

Sustained attention deals with consistent selective attention maintenance to consider probable developments and changes, while focused or selective attention is defined as focusing the cognitive resources on a task with high priority. Distributed attention is caused based on the individual's ability to simultaneously coping with information of different types. Sometimes, these distinctions may confuse when defining these concepts, which may be caused due to attention to the immediate awakening and consciousness state to the steady state (Vanderhaegen et al. 2020).

1.2 Research hypothesis and objectives

Cognitive functions (e.g. attention, reaction time, and working memory) may serve as important indicators of individual competence among control room operators. However, research is needed to examine how these functions change due to the workload. This study uses cognitive performance and workload measurements to examine the impact of different workload dimensions (e.g., mental, physical, temporal, effort, performance and frustration) on cognitive performance indicators such as sustained attention, reaction time (RT) and working memory. Based on this framework, two hypotheses are tested:

Hypothesis 1: There is a significant correlation between cognitive performance indices before and after work.
Hypothesis 2: Weighted workload and its dimensions affect cognitive functions (i.e., sustained attention, reaction time (RT) and working memory).

2 Materials and methods

2.1 Methodological approach

o investigate the effect of workload on operators' cognitive functions, an experiment was conducted using a within-participants design. A total of 105 control room operators from the two combined cycle power plants participated in this study. However, having exerted the exclusion criteria such as taking painkillers as well as suffering from psychiatric and systemic diseases (cardiovascular, liver, pulmonary, etc.), only 95 operators were taken into account as the subjects. Participants' age ranged from 31 to 52 years and all of them had normal or corrected (to 10/10) vision acuity and full color vision. All the participants were male and considered as one group.

The Tasks of these individuals were as follows: continuous communication with the National Dispatching Control Center to control the production and condition of units and lines, obtaining the reports from operating operators and reviewing these reports. Making contact with the personnel of the repair department for fixing the possible problems and creating a safe and secure work environment for the repair team as well as issuing various warranties on power lines, generators, transformers and related equipment. Operators in 4 control rooms (in two CCPP) operated in the morning, evening and night shifts.

Based on the requirement of this experiment, the participants were tested in terms of the cognitive functions (sustained attention, reaction time (RT), working memory) at the start (before work shift, 7:30 AM) and at the end of the work shift (15:30 PM).

Continuous performance test (CPT) was performed to evaluate the sustained attention(Roccio and Reynolds 2001) and psychomotor vigilance task (PVT) was used to measure the reaction time (RT) (Kazemi et al. 2016) and finally N-back was conducted to evaluate working memory (Cook 2000). Before starting study, the operator was kept in a quiet room for 10 min and the researcher described the details of the tests to him and In the meantime, the tests were carried out empirically to get acquainted with each of them (Jafari et al. 2014). NASA-TLX Workload questionnaire was given to them at the end of the work shift according to the analysis of the tasks of the control room operators by hierarchical task analysis (HTA). Demographic information such as age, work experience, education and work shift were initially gathered. To observe the ethical issues, the study goals were explained to them, and consent form was obtained from all participants before the study began. The Scientific and Medical Ethics Committee of all study sectors approved the ethical standards of the study (Code of ethics: IR.Modares.rec.1397.033).

Table 1 includes various hypotheses along with independent and dependent variables, and Fig. 1 shows photos from the control rooms.

2.2 Sustained attention

Continuous performance test (CPT) was performed to evaluate the sustained attention. The main purpose of this test is to measure sustained attention, impulse control, or impulsivity.

CPT is a valid and reliable measure to assess sustained attention (Cornblatt et al. 1988) and has been widely used

Table 1 Various hypotheses along with independent and dependent variables

Dependent variables (tests)	Independent variables
Omission error (CPT)	Workload weighted (NASA-TLX)
Commission error (CPT)	Mental demand
Attention percent (CPT)	Physical demand
Reaction time (PVT)	Temporal demand
N Correct (N-Back)	Effort
N Error (N-Back)	Performance
Reaction time (N-Back)	Frustration

to detect attentional performance impairment and inhibition deficits (Gokalsing et al. 2000; Mani et al. 2005).

So far, various forms of continuous performance testing have been developed for therapeutic and research purposes and in all forms, the subjects must for a long time direct their attention to a relatively simple set of visual or auditory stimuli and respond by pressing a key when the target stimulus emerges (Ballard 2001; Halperin et al. 1991; Roccio and Reynolds 2001).

In this version of the test, there are 150 images or numbers as stimuli, 30 (20%) are considered as target stimuli and the remaining 80% are non-target stimuli. The duration of each stimulus is 200 ms and the interval between two stimuli is 1 s. In this test, two types of omission error (OE) and commission error (CE) are scored. OE occurs when the subject does not respond to the target stimulus and indicates that the subject has difficulty understanding the stimulus. This type of error is interpreted as a problem of sustained attention and indicates lack of attention to the stimuli. A CE occurs when the subject responds to a non-target stimulus. This type of response indicates a weak impulse inhibition and is interpreted as a problem with impulse control or impulsivity (Jafari et al. 2014).

The participants were trained on how to initiate the cognitive computer-based tasks to undergo the test. The following scores were considered and recorded: (1) the sum of commission errors; (2) the sum of omission errors (defined as not pressing the key); (3) the number of true answers, and (4) the reaction time (RT) (in millisecond), which was defined as the time interval between the stimulus presentation and button pressing for the reaction.

The RT of individuals in each step was reported by the outputs of the used software and the attention percent (AP) was calculated. Thus, the number of correct responses was divided by the total number of stimuli and the result was multiplied by 100 (Jafari et al. 2014; Mohebian and Dehghan 2017). The stimuli were randomly presented to each individual to prevent the learning effect (Askaripoor et al. 2019).

2.3 Reaction time (RT)

In this study, the Psychomotor Vigilance Task (PVT) on a PC was used to measure the reaction time. This test consists of red circles appearing on the screen randomly distributed over time intervals. Participants were trained to press the key on the keyboard as soon as they saw the stimulus. The software records the RT in milliseconds. If no response were given within 1750 ms, a new time interval would begin and if the participant pressed the key before or after 120 ms from the stimulus presentation, the response would be eliminated and an alert signal would sound. In this study, a personal computer device was used for all participants to eliminate device error and, the mean and standard deviation of RT and numbers of correct responses were recorded as dependent variables (Kazemi et al. 2016).

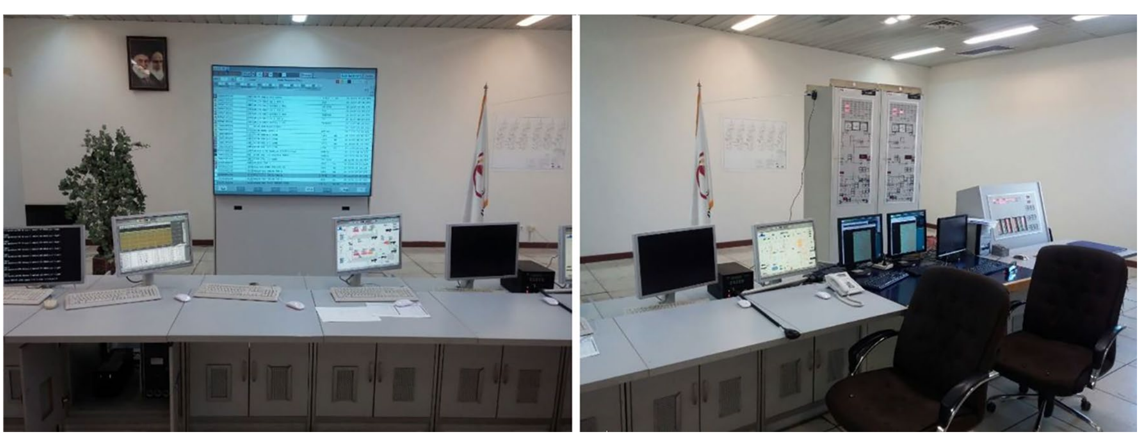

Fig. 1 Photos from the control room of the studied power plants (operators' images were removed due to ethical considerations)

2.4 Working memory

The N-back working memory test has been used to evaluate the working memory (Cook 2000). This test has three levels in terms of complexity and while the first level is the simplest one the third level is more complex than the others. Many individuals could not complete the third level correctly (Ayaz et al. 2007; Grissmann et al. 2017). Second level is also fairly complex but it is expected that most of the participants could accomplish that successfully. In addition, the previous studies which conducted the test in three complexity levels were reviewed (Bottenheft et al. 2020; Izzetoglu et al. 2007; Sumińska et al. 2020) and as a result, the second level was finally selected to be used. According to the test instruction, during 5 min, a number of 120 sequences will appear in the center of the computer screen, with 1500 ms time interval. The participant must compare the last number shown with the two preceding numbers, if the compared numbers are the same, the correct key on the keyboard is quickly pressed, and otherwise the incorrect key is pressed. The number of correct responses (score) and response time (milliseconds) were recorded as dependent variables in this study. This test has a very good reliability for evaluating working memory (Chen and Mitra 2009; Kazemi et al. 2016).

2.5 Hierarchical task analysis (HTA)

In this step, the operators' tasks in control rooms were divided into the detailed level of activities using hierarchical task analysis (HTA). HTA encompasses ideas which were developed by Annett and Duncan (Annett 2003) and totally proved as a public task analysis used to analyze and investigate the partial components of a work and a tool for describing a task in terms of purposes and secondary aims. According to HTA, a particular work is divided into subtasks and working steps. The working step is also divided into a smaller task level. Based on the definition, each of the working steps can be determined by the operator's tasks (Li et al. 2020).

2.6 Workload

The National Aeronautic and Space Administration Task Load NASA-TLX questionnaire was used to evaluate participants' workload (Hart and Staveland 1988).

This index is commonly used for workload evaluation (Noyes and Bruneau 2007; Pickup et al. 2005), which showed high convergence when compared with the other methods of workload assessment (Rubio et al. 2004). The evaluation included scales, which were divided into a hundred equal distances, and manually marked and rated from good to poor or low to high. This scale includes six sub-dimensions or sub-scales: mental demand, physical demand, temporal demand, effort, performance, and frustration. First, the main tasks were inserted on the sheets according to job analysis. Then, they were asked to define the desired number for each task, which clarifies the scales for tasks based on the sub-scales and finally asked them to order the scales in a pairwise way in terms of importance and then draw a line around them. It was used for identification of the dissimilarities in the work definitions among individuals, dissimilarities in the resources of workload among tasks, and to define the scale weight (Dorrian et al. 2011). Mohammadi et al. conducted a study in which they confirmed the reliability and validity of the Farsi version of the index (Mohammadi et al. 2013).

2.7 Statistical analysis

For data analysis, SPSS software version 20 was employed. To assess the normality of the variables, Kolmogorov–Smirnov was utilized. To compare the results before and after the shifts, paired *t* test was done. In addition, demographic data were analyzed using descriptive statistics. Multiple linear regression and Spearman correlation analysis were done to investigate the relationship between workload and overall cognitive performance.

3 Results

The present study was performed on 95 control room operators with a mean age of 38.21 and a standard deviation of 3.2, which indicates the population under study is middle-aged. The results also showed that the mean work experience was 12.7 with a standard deviation of 2.9 years, the highest bachelor's degree with 72%, followed by the master's degree with 26% and 2% PhD, respectively. 96% of participants are married.

Tables 2 and 3 show the results from the cognitive tests and workload measurements. According to Table 2, while the RT and attention percent (AP) were reduced at the end of shift, the CE (response to incorrect target) and OE (observation of target and no response) were increased.

In PVT test, a decrease in RT was seen at the end of shift; however, this decrease was not significant. Likewise, in the working memory test, the number of correct responses at the end of the shift has significantly decreased and consequently the number of incorrect cases has increased. The RT has also increased significantly at the end of the shift.

The mental workload on Check and control tasks (92.17 ± 4.38), decisions about abnormal conditions (90.16 ± 5.71) and reporting (85.09 ± 3.25) is high (Table 2). The task of communication and coordination in terms of temporal demand (71.66 ± 7.3) and performance

Table 2 Mean and standard deviation of reaction time, errors and attention percent at the beginning and end of the shift

Test	First of shift	End of shift	*p*
CPT			
Omission error (OE)	0.096 ± 0.242	0.403 ± 0.455	< 0.001
Commission error (CE)	0.098 ± 0.216	1.28 ± 0.851	< 0.001
Attention percent (AP)	99.01 ± 0.958	97.02 ± 1.87	< 0.001
PVT			
Reaction time (RT)	333.34 ± 35.51	321.82 ± 47.08	0.11
N-Back			
N Correct	81.26 ± 22.43	69.63 ± 22.41	< 0.001
N Error	25.07 ± 15.92	31.19 ± 17.46	< 0.001
Reaction time (RT)	684.34 ± 156.04	730.46 ± 161.14	< 0.001

(68.04 ± 4.92) have higher values compared to other tasks. The task of checking and controlling has the highest weighted workload (84.27 ± 6.48) (Table 3).

Pair T test for the data obtained from the cognitive performance at the beginning and the end of the shift showed that the difference in RT and CE, OE and AP was significant. According to Table 4, Spearman correlation analysis of the cognitive performance variables at the beginning of the shift indicates that AP has a significant inverse relationship with OE and CE ($r = -0.848$** and $r = -0.389$**). The highest percentage of inverse and significant correlation was observed between the AP and the CE at the end of the shift ($r = -0.971$**).

Correlation of workload items with cognitive performances is shown in Table 5. Cognitive performance differences at the beginning and end of the shift was considered

Table 3 Evaluation of workload of the main tasks of the control room operators

Task	Mental demand	Physical demand	Temporal demand	Effort	Performance	Frustration	NASA weighted
Check and control	92.17 ± 4.38	60.49 ± 6.29	70.15 ± 6.13	66.72 ± 5.89	67.58 ± 4.86	52.62 ± 4.65	84.27 ± 6.48
Reporting	85.09 ± 3.25	59.85 ± 6.26	69.43 ± 7.1	65.16 ± 6.46	67.26 ± 4.68	51.49 ± 4.68	74.56 ± 7.34
Communication and coordination	77.17 ± 4.91	59.5 ± 6.13	71.66 ± 7.3	64.89 ± 6.15	68.04 ± 4.92	53.15 ± 4.24	72.69 ± 6.79
Supervision on local operators	70.9 ± 12.45	59.11 ± 5.91	69.92 ± 6.31	65.73 ± 6.31	67.54 ± 3.99	52.62 ± 5.52	72.82 ± 8.36
Work permit	85.03 ± 6.08	60.29 ± 5.68	69.4 ± 6.1	64.53 ± 5.9	66.79 ± 4.12	52.72 ± 5.78	78.68 ± 10.72
Operation and decisions about abnormal conditions	90.16 ± 5.71	60.84 ± 6.41	70.88 ± 5.96	65.04 ± 7.3	67.53 ± 4.62	52.13 ± 6.78	74.07 ± 7.05
Training and filling the forms	84.23 ± 3.01	60.28 ± 5.89	70.16 ± 6.44	64.48 ± 8.65	66.92 ± 5.32	52.29 ± 4.79	72.74 ± 8.33
Mean	85.83 ± 11.57	60.05 ± 23.17	70.22 ± 21.56	65.22 ± 24.86	67.38 ± 23.12	52.43 ± 26.36	75.69 ± 14.23

Table 4 The correlation between cognitive performance at the beginning and end of the shift (the values shown by *r*)

	First of shift				End of shift			
	OE	CE	RT	AP	OE	CE	RT	AP
First of shift								
OE	1							
OE	0.106	1						
RT	0.028	0.115	1					
AP	−0.848**	−0.389**	−0.021	1				
End of shift								
OE	0.306**	0.003	−0.072	−0.282**	1			
CE	0.320*	0.069	−0.021	−0.327**	0.139	1		
RT	0.021	0.104	0.431**	−0.051	0.173	0.018	1	
AP	−0.360**	−0.083	0.031	0.368**	−0.331**	−0.971**	−0.063	1

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

Table 5 Examination of the correlation between dimensions of workload and cognitive performances

	Workload						
	Mental demands	Physical demands	Temporal demands	Performance	Effort	Frustration	Workload weighted
CPT							
OE	0.101	0.009	0.120	0.142	−0.037	0.061	0.067
CE	−0.140	−0.141	−0.085	0.00	−0.171	0.005	−0.174
RT	−0.063	−0.125	−0.265**	−0.219**	−0.255**	0.016	0.266**
AP	0.061	0.031	0.268**	0.049	0.132	−0.095	0.217*
PVT							
RT	0.05	0.015	0.016	0.067	0.021	0.073	0.075
N-Back							
N Correct	0.178	0.166	0.195	0.096	−0.005	−0.034	0.124
N Error	−0.032	−0.141	−0.193	−0.078	−0.139	0.028	0.214*
RT	0.017	0.213*	0.261**	−0.136	−0.038	0.051	−0.077

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

Table 6 Multiple linear regression analysis to determine the effect of dimensions of workload and cognitive performances

Unstandardized coefficients				
Model	β	SE	*t*	*p*
Constant	0.376	31.480	−2.045	0.244
Mental demand	0.304	0.382	0.797	0.428
Temporal demand	0.105	0.192	0.544	0.005
Physical demand	0.455	0.261	1.741	0.005
Performance	0.515	0.299	1.725	0.088
Frustration	0.272	0.216	1.259	0.211
NASA-TLX weighted	0.128	0.153	0.838	0.004

Table 7 Coefficient of determination results

Model	*R*	*R* square	Adjusted *R* square
1	0.622[a]	0.404	0.435

[a]Prediction:(constant), NASA-TLX weighted, physical demand, temporal demand, effort, mental demand, Frustration, performance

as the criterion for changes to evaluate the correlation. According to the presented results, the dimensions of workload were correlated only with the cognitive performances measured in the continuous performance test and working memory. Temporal demand had a significant relationship with RT and AP ($r = -0.265$) and ($r = 0.268$) and RT in the N-Back test ($r = 0.261$) as well as performance and effort and weighted workload with RT in continuous performance test ($r = -0.219$) and ($r = -0.255$) and ($r = 0.266$). Weighted workload had a significant correlation with the number of errors in the N-Back test ($r = 0.214$) and the physical demand for RT in this test ($r = 0.213$).

According to Table 6, three independent variables (including NASA-TLX weighted, physical demand and temporal demand) significantly affect cognitive performance ($p < 0.05$). The determination coefficients (R^2) of the multiple linear regression are presented in Table 7, which elucidates the variance between the independent and dependent variables. The R^2 value (0.404) implies that 40.4% of the cognitive performance variance can be explained by the three variables of NASA-TLX weighted, physical demand, and temporal demand.

4 Discussion

The purpose of the present study was to investigate the effect of workload on cognitive performance of control room operators. The results showed that workload and its different dimensions affect some measured cognitive performances (RT, AP, CE and OE). Temporal demands had an inverse relationship with RT($r = -0.265$) and a direct relationship with AP ($r = 0.268$); also, performance and effort had a negative effect on the RT($r = -0.219$) and ($r = -0.255$) and weighted workload had a direct effect on that ($r = 0.266$).

As a natural type of data, reaction time values are used to investigate the cognitive processes in the cognitive test performance. RT has been shown to be affected by several measures such as weighted workload, temporal demand, physical demand, effort and performance. Performance accuracy and RT are known as two sensitive mental workload measures, which may be used for complex operations (Jafari et al. 2020; Wei et al. 2014).

The environmental parameters such as noise, illumination, and temperature, that might affect the workload levels (Rolo et al. 2010; Varjo et al. 2015) should also be taken into account during a field study. Therefore, to control these confounding parameters, all the studied individuals were selected from the same work shift.

The comparison of the mental workload in this study showed that the scores of the overall NASA-TLX and its dimensions were higher in the check and control operation than in the other operations.

Operations such as check and control usually entail switching between tasks and are critical tasks in the control room with which many operators are involved on a daily basis. They usually spend a large amount of time on it, which routinely contributes to excessive workload and might contribute to decrease in effectiveness and increase in the time necessary to complete a task.

The subjective nature of the tools for assessing the overall perceived MWL as well as the sensitivity of different aspects of MWL are presumably the critical points that should be considered in such investigations (Mansikka et al. 2019).

Lee and Liu (2003) measured the mental demand and performance by NASA-TLX and concluded that they were the most sensitive dimensions among flight operators (Lee and Liu 2003) Fallahi et al. also reported that almost all of the dimensions investigated by NASA-TLX were considered sensitive in traffic control operations (Fallahi et al. 2016).

As delayed reactions or mistakes made during work might lead to detrimental effects as well as increase in the number of incidents and accidents (Cheng et al. 2017), the concept of cognitive flexibility have been introduced for effective functioning in a dynamic environment. It enables the operators in decision-making processes particularly when it comes to switching instantly to another task that is more urgent (Sumińska et al. 2020).

According to Table 1, there was a significant difference between the values of cognitive performance variables (OE, CE and AP) and in N-back (N Correct, N Error, RT) at the beginning and end of the shift. AP and N Correct at the end of the shift were reduced, but CE and OE and RT and N Error increased at the end of the shift.

The results from the present study were consistent with the previously published studies on cognitive performance, though the same variables have not been assessed in a field study (Machi et al. 2012; Rouch et al. 2005; Shwetha and Sudhakar 2012). Machi et al. studied the emergency ward physicians and proved a significant short-term memory decline at the end of shifts, including both night and day shifts (Machi et al. 2012), which may be caused by circadian rhythmicity disturbance in the shift workers besides the long working time fatigue (Kazemi et al. 2016).

The level of human–machine interfaces (HMI) and the related workload relies on the automation level and the role of the operators of the control room besides other controllers in the control room. These results prove the mentally demanding and complexity of this job.

Managing the interaction between human–machine system and the human operator is the key point in designing a system. Accordingly, in both simulated and real contexts, specific and efficient methods of training should be employed to adapt the human operator to such system (Vanderhaegen 1997, 1999a).

The present study results reveal that the RT and the operator's error rate are significantly affected by increased work demand, which may be attributed to the induced stress.

Sliwinski et al. (2006) investigated between and within-person change in the experienced daily stress and cognition over time. They found a slower RT in highly stressful days in comparison with low-stress days. They concluded that the stress-induced cognitive interference competes for resources of cognitive attention (Sliwinski et al. 2006). Andel et al. (2016) reported that jobs with higher strain levels low control levels do not lower the cognition level when working, though, at retirement, it is associated with worse memory and more rapid cognitive decline after retirement (Andel et al. 2016).

Increased commission and omission error and reduced percentage of attention can be attributed to the effect of high mental workload; in fact, when a simple task is given to a person and there is no time pressure, they will not need to use specific strategies to do the job properly and they will probably do it negligently. Conversely, when mental workloads increase due to time pressure, people perform their work with greater error and less attention (Gonzalez 2005; Schnotz and Kürschner 2007). This indicates that the greater the individual's attention during the test, the lower the number of errors and vice versa. Attention is closely related to reaction time, namely the higher the level of attention in the test participants, the shorter the reaction time. The reverse is also true, and with a lower level of attention of individuals, longer reaction times are recorded (Karwowski 2001; Martin et al. 2019). The participant's further attention was devoted to a more complicated cognitive task seen in deprived or normal situations (Chee and Choo 2004).

In general, when the level of received information runs over the processing capacity of the operators (i.e., when the workload is increased), they usually come up with delays in responding to the stimuli (Ryu and Myung 2005). The extended and extra working hours have been shown to contribute to excessive fatigue, leading to committing errors and decreasing productivity (Barger et al. 2006).

One of the most important symptoms of mental fatigue is attention disorder. The time pressure includes the conflict between the time taken to complete the job and the actual time needed to perform the job which leads to many psychological reactions. In particular, it increases the anxiety of the individual and consumes more resources. This would increase the mental workload and ultimately reduce the performance and accuracy of the response (Backs and Seljos 1994; Inzana et al. 1996). In particular, time pressure has been shown to be a stressor in the workplace, where time may be part of a mediating process that affects control perceptions (Koslowsky et al. 2013).

Due to the change in the scores of cognitive tests at the end of the shift and the fact that we only focused on the day shifts (7:30–15:30), while the work process of the power plant as stated in the introduction was in 5 shifts rotation and the working operators next was tomorrow evening, therefore, the followings are commented:

The imbibition of reaction is a part of operational functions, which is reduced among the shift workers (Baddeley 2002). This fact implies that it might not be possible for them to do their operational functions properly. Some shift workers cannot adapt to the shift work and hence are more vulnerable to cognitive function deterioration, which may be proved by cognitive flexibility decline and schematic reaction inhibition deficiency (Cheng et al. 2017).

According to the results of the present study, the operator's performance is significantly reduced during work shift operations at the beginning and the end of the working shifts. Thus, the performance of the operator was proved as a sensitive measure in the mental demands alterations.

The excessive mental work load compared to other dimensions in the present study highlights the complexity of the human information processing system and shows the importance of investigating this parameter in combination with other techniques (Carayon et al. 2015; Colle and Reid 1998). Difficulty of task, time of day and psychological level of participants in previous studies have been effective factors in mental performances (Correa et al. 2016; Huiberts et al. 2015).

Through studying these factors, we make the following contributions: a novel study of the relationship among workload and cognitive performance, for specific jobs and operation such as combined cycle power plant control room operation. In the current study, various specific exclusion/inclusion criteria were used to control the influence of a number of individual differences, including age, and work experience, on cognitive performance and workload both within and between individuals. Thus, more studies are required to consider individual differences and their role in cognitive performance in the control room operation. Furthermore, the impact of gender on the mental workload and cognitive responses may not be addressed since all of our participants were male operators.

In addition, due to the limited time and scope of the study, it was not possible to perform psycho-psychological tests. It is suggested that this study be replicated with a larger sample and the addition of a section on psycho-psychological measurements.

5 Conclusion

Numerous studies have been conducted in laboratory environments in which individuals performed work tasks to evaluate or classify different levels of workload and cognitive performance. The findings of such studies cannot necessarily be used in real work environments. Thus, this study was conducted in the work environment and real-time conditions. The results showed that excessive burden of mental work increased workload, influenced the CE, and decreased the AP. RT variable is also directly affected by weighted workload, temporal demand, physical demand, effort and performance. It can be concluded that the RT is greatly affected by the workload and much attention should be paid to the sensitivity of the operating speed in the control rooms.

Declarations

Conflict of interest The authors declare that they have no conflict of interest (financial or non-financial).

Ethical statement This study was an occupational health PhD thesis in Tarbiat Modares University. We did not have any source of funding. The study has been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. The study was approved by the ethics committee of the university. An informed consent was obtained from all the participants.

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