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Effects of mental workload on physiological and subjective responses during traffic density monitoring: A field study

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This study evaluated operators' mental workload while monitoring traffic density in a city traffic control center. To determine the mental workload, physiological signals (ECG, EMG) were recorded and the NASA-Task Load Index (TLX) was administered for 16 operators. The results showed that the operators experienced a larger mental workload during high traffic density than during low traffic density. The traffic control center stressors caused changes in heart rate variability features and EMG amplitude, although the average workload score was significantly higher in HTD conditions than in LTD conditions. The findings indicated that increasing traffic congestion had a significant effect on HR, RMSSD, SDNN, LF/HF ratio, and EMG amplitude. The results suggested that when operators' workload increases, their mental fatigue and stress level increase and their mental health deteriorate. Therefore, it maybe necessary to implement an ergonomic program to manage mental health. Furthermore, by evaluating mental workload, the traffic control center director can organize the center's traffic congestion operators to sustain the appropriate mental workload and improve traffic control management.

1. Introduction

Because of the development of mechanization and automation, mental workload (MWL) is one of the most important issues in the area of work systems (Nachreiner, 1995). MWL or just workload “is the general term used to describe the mental cost of accomplishing task requirements” (Hart and Wickens, 1990). A workload can be either physical or mental, although these are always connected and cannot be completely separated when a subject performs a particular task (Lean and Shan, 2012). Human operators are vital components of various systems, maintaining their performance at an appropriate level. Thus they are commonly found in control workplaces, often working there for several years (Balfe et al., 2015). The more demanding and complex the task, the more the operators must work to accomplish the task (Vidulich and Tsang, 2014). In such situations, MWL increases and the operators may demonstrate delayed information processing or even fail to react at all to the received information because the amount of information outstrips their capacity to process it. In contrast, when their MWL decreases from a suitable level, they feel bored and tend to make errors (Ryu and Myung, 2005). Increased demand on available resources can cause human operator overload (Dadashi et al., 2013). In such cases, the operator experiences an extensive level of MWL in his or her daily work without enough time to rest, and health problems such as chronic stress, depression, or burnout can occur (Cinaz et al., 2013), which can influence the worker's performance and well-being (Johnson and Widyanti, 2011). Van Daalen et al. (2009) indicated that a mismatch between task demand and the capabilities of the worker can cause work-related stress. The impact of MWL on cardiovascular indices has been widely studied during the performance of laboratory tasks (Backs and Seljos, 1994;

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Veltman and Gaillard, 1996), simulated work (Brookings et al., 1996; Veltman and Gaillard, 1998; De Rivecourt et al., 2008; Dijksterhuis et al., 2011), and real work conditions (Wilson, 1992; Roscoe, 1992). Furthermore, optimizing the MWL experienced by a system operator could reduce the possibility of human errors and the cost of training, improve systems' safety and performance, and achieve operator satisfaction (Jo et al., 2012; Mitchell, 2000; Lebiere, 2001; Di Stasi et al., 2011).

Several studies have used performance-based (e.g., dual-task), physiological (e.g., heart-rate variability or HRV) and subjective (e.g., rating scale) methods to evaluate MWL (Johnson and Widyanti, 2011). The subjective rating scale is an important tool that can be applied globally to evaluate the MWL of a system's operators (Rubio et al., 2004). Nygren (1991) explained that the most extensively used subjective rating scales that have received significant attention are the subjective workload assessment technique, or SWAT (Reid and Nygren, 1988), and the NASA-Task Load Index (TLX) (Hart and Staveland, 1988). Psychophysiological measures allow for a more objective workload assessment and can provide “real time” evaluation, thus allowing the system designer to quickly and accurately identify usability problems as they occur (Tran et al., 2007). Heart rate or HRV acquired from an electrocardiogram (ECG) is widely used and has a long history in the evaluation of MWL (Jorna, 1992, 1993; Roscoe, 1992, 1993). HRV is measured in terms of both time and frequency (Goldstein et al., 2011). The HRV technique is very popular because the ECG signal recording is noninvasive and safe, causing no injuries or pain to humans (Reyes del Paso et al., 2013). There is limited information on muscle fatigability, with tasks consisting of concurrent physical work and MWL (Mehta and Agnew, 2012). Electromyography (EMG) has been suggested as a measure of physical work and MWL, because increased muscular tension has been shown to be related to both kinds of workload (O'Donnell and Eggemeier, 1986). EMG is the most frequently used method to measure muscle activation and fatigue (Zadry et al., 2011). Changes in EMG activity (a decrease in mean power frequency, MPF, and/or an increase in EMG amplitude) during standardized voluntary contractions have been widely employed as indicators of muscle fatigue (Madeleine et al., 2002; Dimitrova and Dimitrov, 2003).

Researchers have developed most of these methods and tools in laboratory-based studies and then applied their findings to performance response in real working conditions. If the scientific assessment tools and methods are used in field research, their findings may be more valuable than research conducted in a laboratory. MWL is an issue that affects work performance (Oron-Gilad et al., 2008); therefore, the field evaluation of MWL is important. The operators of control centers perform basic activities, such as monitoring the functioning of the substation, in which it is essential to make decisions and process information continuously (Vitório et al., 2012).

The city of Mashhad is one of the 163 most populated cities in the world. Due to the accelerated growth of its urban population (2.63 million citizens in 2007), an increasing number of cars, and the attraction of more than 32 million pilgrims and tourists each year (as the second largest holy city in the world), Mashhad faces traffic problems (Azari and Arintono, 2012). To solve these problems, the city implemented an Intelligent Transportation System (ITS), which can be defined as “the application of computing, information, and communications technologies to the real-time management of vehicles and networks including the movement of people, goods, and services.” The ITS consists of a wide range of electronic technology, and wired and wireless communications based information. It includes a major subsystem called the Advanced Traffic Management System (ATMS). The ATMS can control traffic density in real time, and it aims to minimize traffic load while the movement of people and goods increase, to improve traffic density, and to focus on and manage travel demand (Samadi et al., 2012). To reach these goals, operators of traffic control centers (TCCs) often face difficult task conditions when non-recurrent, non-predictable traffic density occurs (e.g., due to an incident or unexpected weather conditions). In these cases, in addition to local measures, an intervention at the network level is usually necessary to manage traffic density and return to a normal traffic situation. This involves the TCC operators redirecting traffic density in a larger part of the network to decrease the effects of traffic density. The operator has to assess the severity of the traffic density, predict the most probable evolution of the state of the network, and select the most appropriate actions. This complex task requires particular knowledge and a great deal of experience, so each operator usually requires extensive training. Therefore, operators at TCCs continuously monitor traffic densities which are unstructured and generally different (Hegyi et al., 2001). Usually, operators managing complex work environments are exposed to different stressors, which can present risks to safety, performance, and well-being, as well as pose long-term consequences for their health (Saueret al. 2013). Thus it is important to evaluate MWL in real working conditions to understand how to prevent mental disorders and maintain mental health; however, most research has evaluated different levels of MWL in laboratory conditions (Cinaz et al., 2013). The ECG and EMG measurements can be carried out during real work tasks, at least in jobs where most work is performed at a computer in an office-like environment. One critical area involves operators that work in TCCs, as early identification of their MWL is important. This information can be used to promote a good work environment and ergonomics to optimize work demand levels so that the risk of mental disorders and human errors decreases. In this study, which aimed to make recommendations to prevent mental disorders and to promote the mental health of operators, we used a subjective workload assessment (NASA-TLX) and physiological measures (e.g.HR, HRV and EMG) to evaluate operators' MWL during real working conditions at a city TCC to understand and quantify the MWL value.

2. Methods

2.1. Participants

Sixteen healthy male operators (mean age 29.4 $\pm$ 2.61 years) participated in the study. They were paid for their participation in the experiment. They were right-handed with normal or corrected-to-normal vision and hearing, and they had no diseases. All operators read and signed a consent form before the experiment. The experiment was designed to investigate MWL in resting, low traffic density (LTD), high traffic density (HTD) and recovery conditions.

2.2. Procedure

The TCC (Fig. 1) operates 24 h a day, Saturday to Friday, with an on-call team available 24 h a day, 7 days a week. The operators almost constantly monitor the traffic density of intersections from morning to night, including weekends, and if an accident or special event occurs, they try to reestablish a normal traffic pattern in the city. There is a hierarchical environment at this TCC. During each shift, at the first level, four operators with less work experience perform the monitoring task. Three operators with more work experience work at the second level, and the third level is allocated to the shift supervisor, who usually has the most experience. Therefore, the supervisor usually manages the activities of seven operators in each work shift. The supervisor superintends car accidents/incidents and camera and sensor failures at intersections.