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Analysis of the sensitivity of heart rate variability and subjective workload measures in a driving simulator: The case of highway work zones

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ABSTRACT

Heart rate variability and subjective workload measures are extensively used to determine workload during driving. However, the sensitivity of heart rate and workload measurements in simulated driving environments is mostly unknown and can significantly affect the experiment results. The objectives of this paper are to determine how heart rate variability and subjective workload are affected in simulated highway work zones and study the relationship between heart rate variability, subjective workload, and driving performance indicators in simulated driving environments. Conventional lane merge (CLM), joint lane merge (JLM) and a road with no work zone are modeled with high and low traffic densities in a full-size driving simulator. NASA-TLX subjective workload measures and heart rate variability measures of root mean square of successive heartbeat differences (RMSSD), low frequency (LF), high frequency (HF) and the ratio of low frequency to high frequency (LF/HF) are collected in 30 participants. Variability in steering angle, braking and speed are used as driving performance indicators. Results show that compared to no work zone, participants experienced higher mental, temporal, and overall workload in the CLM scenario and poorer driving performance ratings in the CLM and JLM scenarios. All workload measures except for performance were higher with high traffic density. However, heart rate variability measures were not sensitive to the differences in driving scenarios and traffic densities. Pearson correlation coefficients indicated an association between RMSSD and all the subjective workload measures ($r > 0.21$) except performance, and between LF, HF, and LF/HF ratio and mental workload ($r > 0.21$). Steering angle variability was slightly correlated with LF, HF, and LF/HF ratio ($r > 0.16$), but brake and speed variability were not associated with physiological outcomes.

In conclusion, the subjective workload was higher in simulated work zones and under higher traffic density, but heart rate measures were largely unaffected.

1. Introduction

Drivers traveling through highway work zones are exposed to a variety of objects and traffic signs that convey different information (Oppenheim et al., 2010; Oppenheim and Shinar, 2012). To make proper decisions and perform appropriate actions, a driver should continuously filter what seems to be relevant information from the driving environment. According to Michon (1985) and de Waard (1996), the complexity of the driving environment can affect the information processing and attention of drivers. With the increase in a driver's information input (i.e., the information conveyed to drivers through signs, signals, other cars, flaggers, etc.), the mental capacity reduces (depending on the individual abilities, expectancy, and experience), resulting in the feelings of pressure and stress (Heger, 1998). Workload is a term that represents the cost of accomplishing a task (Hart, 2006) and can be defined as the amount of information-processing resources used per unit time to meet the level of performance required for the task (Wickens and Hollands, 2000). The literature on driver safety and driving workload confirm that accident risks and driver workload are strongly associated (Kantowitz, 1987; Ibeas et al., 2014), and increasing the driving

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workload can result in the degradation of driving performance efficiency (Teh et al., 2014).

To increase the road and driver safety, the driving workload should not exceed drivers' information processing capacities (Fastenmeier and Gstalter, 2007). In a highway work zone, a driver may occasionally experience periods of particularly high task demand and fluctuations in information processing capacity. If a task demand (e.g., merging from a closed lane into an open lane) exceeds drivers' information processing capacity, drivers may fail to capture the information that is critical to their safety (e.g., noticing that the front car slowed or stopped), resulting in accidents and fatalities.

Researchers in the field of transportation safety use workload measurements extensively. For example, Brookhuis and de Waard (2010) reported that driving on busy road results in a higher subjective mental workload than driving on a quiet motorway. Hao et al. (2007) studied the effects of different traffic densities in a driving simulator on the drivers' physiological and subjective workload (NASA-TLX) and found that on average, with the increase of traffic density the average heart rate, and LF/HF ratio increased significantly, and participants reported higher ratings for the TLX measures. Schiessl (2008) investigated if incremental changes in external stress factor levels such as traffic density in a driving simulator can be detected by subjective ratings of workload and heart rate. She found that higher traffic densities led to higher workload ratings. However, as opposed to Hao et al. (2007), heart rate measurements were not statistically different in different traffic densities (Schiessl, 2008).

Driving simulators provide a controlled environment for conducting traffic research. However, review of the literature shows mixed results for the physiological measures of the workload when they were collected in a simulated environment. The objective of this paper is to determine (1) which measures of workload are sensitive to the changes in the driving simulator, and (2) if there are any association among subjective workload, physiological workload and performance measures when used in a driving simulator.

2. Methods of measuring workload

Three categories of workload measurements that have been widely used in the literature to evaluate driver workload are subjective workload, physiological workload and performance measures (primary task performance measures, secondary task performance measures, and reference tasks). In subjective measures, operators perform a task and give feedback on the workload measures based on their experience. The most frequently used subjective workload measurement technique is the NASA-Task Load Index (Hart and Staveland, 1988). NASA-TLX is a questionnaire consisting of six components: mental demand, physical demand, temporal demand, performance, effort, and frustration. Completing the NASA-TLX is a two-step process. In step 1, participants perform a task (similar to the primary experimental task), and after the completion, they are asked to make a pairwise comparison of those six components (15 comparisons in total) and select the one they experienced more when performing the sample task. These comparisons are used to determine a weighting factor for each component. In the second step, at the end of each experimental stage, participants are given another form to quantify the intensity of each component. This is done by using a 12 cm visual-analog bipolar scale ranging from low to high. The workload is then defined by the product of the weighting factor of each component by its respective intensity.

The primary advantages of subjective workload measures are that they are provided directly by the operators, they can be collected after the task is done, and they are relatively straightforward and inexpensive to collect. The disadvantages of subjective workload are that they cannot be collected in real time, and the results fluctuate over time. Furthermore, operators are sometimes unaware of their internal changes, and results can be biased by factors other than workload (e.g., psychosocial environment.) (Casner and Gore, 2010).

Many scientists prefer physiological methods of measuring workload over subjective measures because they do not require a direct response from the person, and as opposed to the subjective measures that are based on operators' feelings and experience during the task, the results are representative of the actual task workload (Miller, 2001). In physiological methods, the response of the body to external sources of workload is measured and used as indicators of physical and mental workload (de Waard, 1996). Some of the frequently used physiological measures are cardiac activity, respiratory activity, eye activity, speech activity and brain activity. Cardiac activity is the most common method of measuring workload in driving and aviation experiments (Roscoe, 1992; Souvestre et al., 2008; Hoover et al., 2012; Durantin et al., 2014) and is measured through heart rate, heart rate variability (HRV), and blood pressure (Hoover et al., 2012). To determine HRV, the fluctuations in heartbeats are commonly analyzed in two different domains; time domain and frequency domain. The time-domain method is the most straightforward method to measure heart rate variability and is applied directly to successive normal inter-beat intervals (NN) (Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996). Literature shows that the root mean square of successive heartbeat differences (RMSSD) is one of the most robust time domain measures of workload (Mehler et al., 2011).

In the frequency domain method, a spectrum is calculated from the inter-beat (RR) interval series (where R is a point corresponding to the peak of the QRS complex of the ECG wave). Then, this spectrum is divided into three parts. Very-low-frequency (VLF) which ranges from 0 to 0.04 Hz, low-frequency (LF) which ranges from 0.04 to 0.15 Hz, and high-frequency (HF) which ranges from 0.15 to 0.4 Hz (Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996; Mehler et al., 2011; Tarvainen et al., 2014). Research shows that an increase in LF is associated with the sympathetic activity (mental demand) and reduction in HF is linked with parasympathetic activity (physical demand) (Kamath and Fallen, 1993; Wang et al., 2005). Moreover, an increase in the LF/HF ratio is an indicator of increased mental workload (Hjortskov et al., 2004; Durantin et al., 2014).

Some early studies found that heart rate and heart rate variability correlate with workload (Mulder, 1986; Vicente et al., 1987; Metalis, 1991). The results of these studies showed that with the increase in mental workload, heart rate increases, and heart rate variability decreases. One significant advantage of using physiological measures of workload is their unobtrusive nature that obviates a researcher from performing a secondary task or getting feedback from the operator. However, as a downside, mixed results have been reported in the literature indicating that the theory behind physiological measures is not fully developed and still suffers from epistemic uncertainty (Casner and Gore, 2010).

The third category of workload measures is performance measures. Performance measures show how performance is affected if a criterion in the task is changed (e.g., how speed, the number of brakes, etc. are changed when the difficulty of driving task is increased?). Research shows that one drawback to using performance measures is the insensitivity of some of the measures, such as speed, to the state and condition of the driver. For example, a simple driving task that requires low workload can result in a good