Biological Psychology 108 (2015) 115–125

Contents lists available at ScienceDirect

Biological Psychology

journal homepage: www.elsevier.com/locate/biopsycho

Physiological responses related to moderate mental load during car driving in field conditions

Henrik Wiberg[a], Emma Nilsson[a], Per Lindén[a], Bo Svanberg[a], Leo Poom[b,*]

[a] Volvo Car Corporation, Research and Development, Gothenburg, Sweden
[b] Department of Psychology, Uppsala University, Box 1225, SE-751 42 Uppsala, Sweden

ARTICLE INFO

Article history:
Received 8 August 2013
Accepted 23 March 2015
Available online 6 April 2015

Keywords:
Mental load
Workload
Physiology
Field conditions
Car driving
Multivariate models

ABSTRACT

We measured physiological variables on nine car drivers to capture moderate magnitudes of mental load (ML) during driving in prolonged and repeated city and highway field conditions. Ecological validity was optimized by avoiding any artificial interference to manipulate drivers ML, drivers were alone in the car, they were free to choose their paths to the target, and the repeated drives familiarized drivers to the procedure. Our aim was to investigate if driver's physiological variables can be reliably measured and used as predictors of moderate individual levels of ML in naturally occurring unpredictably changing field conditions. Variables investigated were: heart-rate, skin conductance level, breath duration, blink frequency, blink duration, and eye fixation related potentials. After the drives, with support from video uptakes, a self-rating and a score made by external raters were used to distinguish moderately high and low ML segments. Variability was high but aggregated data could distinguish city from highway drives. Multivariate models could successfully classify high and low ML within highway and city drives using physiological variables as input. In summary, physiological variables have a potential to be used as indicators of moderate ML in unpredictably changing field conditions and to advance the evaluation and development of new active safety systems.

1. Introduction

Mental load (ML, as used here, includes both cognitive load and stress) is an important psychological construct in ergonomics, and high ML is associated with increased risk for mistakes and accidents during activities such as car driving. If reliable connections can be demonstrated between these physiological variables and the amount of ML a driver experiences then they have potentials as possible signals for the car-driver system to increase safety, such as driver fatigue warning systems and other systems detecting drivers' mental state, and to advance the development of technical safety solutions in cars without having to be part of the technical solution. For example, attempts in this direction have been made to measure driver's blink duration to estimate drowsiness (Sugiyama et al., 1996), and using EEG signals for an Adaptive Task Allocation (ATA) (Shengguang, 2011). The standard procedures where development and evaluation is typically performed is in controlled car driving simulator environments or controlled real driving with secondary tasks, distraction, follower in the car, and/or pre-specified routes where external events are used to specify different levels of ML (e.g. Collet, Petit, Priez, & Dittmar, 2005; Collet, Clarion, Morel, Chapon, & Petit, 2009; Hagemann, 2008; Healey & Picard, 2005; Johnson et al., 2011; Reimer & Mehler, 2011; Richter, Wagner, Heger, & Weise, 1998; Mehler, Reimer, & Coughlin, 2012; Schneegass, Pfleging, Broy, Heinrich, & Schmidt, 2013; Sonnleitner et al., 2014; Solovey, Zec, Garcia Perez, Reimer, & Mehler, 2014), and may not be applicable to naturally occurring unpredictable changing field conditions where ML varies within moderate ranges. We examined if drivers physiological variables can be reliably assessed and used to measure moderate levels of ML in naturally occurring unpredictable changing field conditions, where drivers are not under direct observation. In the following the terms high ML and low ML specify moderate magnitudes that does not necessarily degrade driving performance, and we do not evaluate low ML as something desirable and high ML as something that should be avoided. Reliable measures of ML within these intervals will make it possible in future studies, and car systems, to determine if drivers ML fall into appropriate ranges.

We wanted the driving to be as natural as possible given the circumstances with the measuring equipment. The drivers were unaffected by the presence of experimenters and were alone in the

* Corresponding author. Tel.: +46 18 471 21 27.
E-mail addresses: hwiberg@volvocars.com (H. Wiberg), leo.poom@psyk.uu.se (L. Poom).

http://dx.doi.org/10.1016/j.biopsycho.2015.03.017
0301-0511/

car during the drives, and no artificially imposed distractions or tasks were used to manipulate ML. The drivers were not required to do additional tasks to manipulate ML, and could choose the route to get to a specified goal. Drivers performed highway and city driving to vary their ML within the normal range. The city and highway drives were further divided into segments of high and low ML based on judgments of the video recordings and interview of the drivers after the drives. The drivers and their ML were evaluated by analyzing actual driver behavior only specified by external circumstances such as the naturally occurring specific road environments and traffic as they performed their drives. Multiple physiological measures were used to collect large amount of individual data for each measure and each driver by measurement equipments attached to their bodies. Repeated drives gave the drivers the opportunity to familiarize with the procedure and get used to the equipment. Physiological data were collected while also the driver and the front and back surrounding of the car were filmed during the drives. These studies were performed during years 2010 and 2011.

2. Ecological validity

Previous psychophysiological measures on drivers in moving vehicles have used secondary tasks, distraction, fixed routes, and/or following observers to manipulate ML (e.g. Collet et al., 2005, 2009; Hagemann, 2008; Healey & Picard, 2005; Mehler et al., 2012; Reimer & Mehler, 2011; Richter et al., 1998; Schneegass et al., 2013; Sonnleitner et al., 2014; Solovey et al., 2014). To our knowledge our study is unique in assessing drivers ML by raters from video uptakes and interview combined with the multiple procedures to optimize ecological validity.

The disadvantage of ecologically valid studies is the lack of control of extraneous variables increasing the noise in data. On the other hand, in search for measures of ML that can be used for car driving applications it is necessary to find measures that are reliable in real driving situations. Although there are advantages in using simulator studies, for example allowing full control with respect to experimental conditions without being risky for the participants (Brookhuis & de Waard, 2010), especially when studying sleepiness during car driving (Ingre, Åkerstedt, Peters, Anund, & Kecklund, 2006), it is not known to what degree results obtained from studies in laboratory environments generalize to naturalistic driving situations. For example, it is difficult to induce stress situations in a simulator that mimics the stress drivers may feel in real driving situations where mistakes can lead to accidents.

3. Modeling mental load

Perceived overall ML is a multidimensional construct influenced by both external demands and individual characteristics such as the familiarity of the task, motivation, arousal, strategies applied, emotional states and personality traits (Humphreys & Revelle, 1984; Ingre et al., 2006; Lykken, Rose, Luther, & Maley, 1966; van Dongen, Baynard, Maislin, & Dinges, 2004). One of the best known models describing ML is the multiple-resource-model where independent limited code specific and sense specific resources are recruited in different stages from sensory encoding to cognitive processing (Wickens, 1984). A later developed model describes how mental energy (e.g. motivation), from a common resource-pool with a limited capacity, is actively used to regulate mental resources (Hockey, 1997). Mental load is experienced when this regulation puts a load on emotional and physiological subsystems and increases activity within the SNS (Kahneman, 1973).

Overall ML can be specified as the proportion of the mental capacity used at the moment (O'Donnell & Eggemeier, 1986; De Waard, 1996), that is, the ratio between the amount of recruited resources (R) as a response to a demand and the capacity (K) available at the moment. Increased ML is experienced during monotony or fatigue due to decreased capacity (De Waard, 1996). The capacity can then be increased and ML reduced by increasing arousal. Also the recruited resources can be increased by mental mobilization or effort (Kahneman, 1973; Mulder, 1980) which then directly increases ML (Vicente, Thornton, & Moray, 1987). Fig. 1 is a graphical description of the model serving as a framework of overall ML.

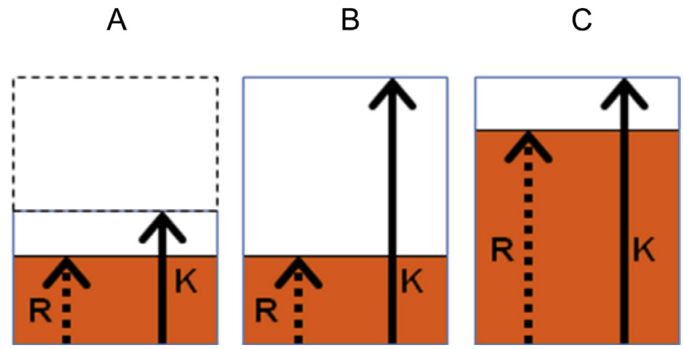

Fig. 1. In this model mental-load (ML = R/K) is the ratio between the resources used (R, dotted arrow), which can be increased by effort, and the available capacity (K), which can be increased by arousal. At low demands (monotonous tasks), the capacity can be increased by increasing arousal (A to B) reducing ML. At high levels of demand capacity reaches its limit and more resources have to be mobilized with effort (C).

4. Types of measures

Measurements of ML can be divided into three main groups, self-reports, physiological measurements and performance measures. Although driving performance may be impaired by high ML, it is not necessary the case that impaired performance means that the driver performs under high ML. Driving performance or risk behavior, which can be influenced by other factors than ML, was not the area of interest in this study. Here ML was assessed by raters judging driver behavior together with factors in the environment. Segments with more traffic and/or pedestrians, crossing traffic, etc. contain more information to process that likely interfere with decision making and were classified as higher ML than segments with less information to process. Self-reports have high face-validity and are therefore frequently used to validate other measures of ML but it is recommended that they are performed after the drive is completed (De Waard, 1996). Here we used a visual analogue scale (VAS) and external raters using video uptakes and interviews to judge drivers ML during their drives, further described in Section 5.7.

Physiological measures of ML are based on unconscious and automatically triggered activity in the autonomic nervous systems (ANS), which is further divided into the parasympathetic (PNS) and sympathetic nervous system (SNS). In short, PNS maintain bodily functions and the SNS is a warning system signaling for example fear or danger, the fight-or-flight response (De Waard, 1996). PNS and SNS can be coupled so that when one system is activated, the second is deactivated, or simultaneously activated, or they can be activated and deactivated independently of each other (Berntson, Cacioppo, Quigley, & Fabro, 1994). Multiple physiological measures of ML have been suggested with variable construct validity such as heart rate (HR), electrodermal activity (EDA), breath duration (BrD), eye blink-frequency (BF), blink-duration (BD), and electroencephalograms (EEG) (e.g. Brookhuis & de Waard, 2010; Brookings, Wilson, & Swain, 1996; Caffier, Erdmann, & Ullsberger, 2003; Daimoto et al., 2007; Healey & Picard, 2005; Miyake et al., 2009; Morris & Miller, 1996; Richter et al., 1998; Sonnleitner, Simon, Kincses, Buchner, & Schrauf, 2012; Stuiver et al., 2012;