International Journal of Psychophysiology 92 (2014) 35–41

Contents lists available at ScienceDirect

International Journal of Psychophysiology

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

Short-term cardiovascular measures for driver support: Increasing sensitivity for detecting changes in mental workload

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ARTICLE INFO

Article history:
Received 7 July 2013
Received in revised form 9 December 2013
Accepted 27 January 2014
Available online 5 February 2014

Keywords:
Cardiovascular reactivity
Heart rate variability
Blood pressure
Driving
Mental workload
Short-term response patterns

ABSTRACT

With on-going increases in traffic density and the availability of more and more in-vehicle technology, driver overload is a growing concern. To reduce the burden of workload on the driver, it is essential that support systems that become available are able to use estimations of drivers' workload. In this paper a short-term cardiovascular approach to assess drivers' mental workload is described using data collected in a driving simulator study. The effects of short lasting increases in task demand (40 s) on heart rate and blood pressure and derived variability measures are applied as indicators of mental effort. Fifteen drivers participated in 6 sessions of 1.5 h in a driving simulator study. Two traffic density levels (7.5 minute segments) were compared in which short-segments (40 s) of fog were used to induce additional workload demands. Higher traffic density was reflected in increased systolic blood pressure and decreased blood pressure variability. Heart rate variability and blood pressure variability measures decreased during driving in fog in the low traffic condition, indicating increased effort investment during fog in this condition. The results show that the described short-term measures can be applied to give an indication of cardiovascular reactivity as a function workload.

1. Introduction

Modern traffic environments are only getting busier, with increasing traffic densities, a growing road network filled with complex interactions, and new in-vehicle devices, such as mobile phones, navigation systems, driver support systems, such as adaptive cruise control, lane departure warning systems or eco-driving advice systems coming on the market. All of this will have impact on drivers' mental workload and may result in safety critical situations (Hancock and Parasuraman, 1992; Stanton and Young, 1998; Salmon et al., 2010; Brookhuis et al., 2001). The concept of mental workload is often used to describe how much of someone's information-processing capacity is needed during task performance and how this is influenced by task demands (De Rivecourt et al., 2008). Resources are considered scarce and when these are exhausted, task performance degradation is likely to occur (Broadbent, 1958; Kahneman, 1973; Posner, 1980; Wickens, 1984; Hockey, 1997; Gaillard and Kramer, 2000). De Waard (1996) explains the negative effects of high workload on driving performance in an adapted version of a model put forward by Meister and reports several studies showing these effects. More recently, Brookhuis and De Waard (2010) stated: “many traffic accidents are caused by, or at least related to, inadequate mental workload, when it is either too low (vigilance) or too high (stress)”. Having adequate measures available for continuous mental workload and short-term effort investment may help manage workload and improve task performance by adapting the way the driver interacts with the in-vehicle systems, based on the measured workload. For example by prioritising tasks secondary to driving or adapting the complexity of the interface of the systems, task demands can be decreased and workload reduced to an acceptable level (Hoogeboom and Mulder, 2004). Measuring workload in this context can be done on the basis of driving behaviour (Young, Birrell and Stanton, 2009) but also by using physiological measures (Fairclough and Venables, 2006; Mulder et al., 2009; Ting et al., 2010). In this context, recent developments in detection methods may be helpful, in which studying heart rate non-intrusively in the car is becoming a feasible option, for example by using photographic pulse detection (Wieringa et al., 2005; Poh et al., 2010) or sensor pads on the steering wheel, which is in development by for example Toyota and Ford (Biometric Technology Today, 2012).

Effects of mental effort on cardiovascular measures have been extensively studied during task performance in laboratory tasks (Backs and Seljos, 1994; Mulder and Mulder, 1987), simulated work (Brookings et al., 1996; Veltman and Gaillard, 1998; De Rivecourt et al., 2008; Dijksterhuis et al., 2010) and during real work (Wilson, 1992; Roscoe, 1992; De Waard et al., 1995; Hankins and Wilson, 1998). In general, during effortful working periods, compared to resting periods or periods of lower workload, a pattern is found for increased heart rate and blood pressure in combination with decreased heart

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http://dx.doi.org/10.1016/j.ijpsycho.2014.01.010

rate variability and blood pressure variability and a lowered baroreflex sensitivity (Reyes del Paso et al., 2004; Wientjes, 1992; Mulder et al., 1992; Mulder and Mulder, 1981).

Some authors have characterized this cardiovascular response pattern as a defence-type reaction or a preparatory fight-or-flight response (Berntson et al., 1991; Jordan, 1990; Mulder, 1980). Such a response pattern is mainly associated with the activation of the sympathetic system, the part of the autonomic nervous system that mobilizes and activates the body, although certainly in the initial reaction phase several signs of vagal inhibition can be found in heart rate and variability measures of heart rate and blood pressure as well (Van Roon et al., 2004). The autonomic space is, in relation to mental effort, often divided in two dimensions; a parasympathetic axis and a sympathetic axis (Berntson et al., 1994). Berntson and colleagues explain how the systems can be independently active, coactive, or reciprocally active. In case of an on-going increase in mental effort, it is mainly the sympathetic system that is responsible for increasing blood pressure to deal with the additional demands on the system. In particular in the initial phase of this response (first few minutes) this reaction to increased mental effort is supported by a strong vagal suppression, resulting in decreased heart rate and decreased variability of heart rate and blood pressure (Backs, 2001; Boucsein and Backs, 2000; Mulder et al., 2000).

Van Roon et al. (2004) were able, using a simulation model of the short-term blood pressure regulation (baroreflex), to explain how these two simultaneous effects of decreased vagal activation and increased sympathetic activation are responsible for this defensive type response pattern of increased heart and blood pressure and decreased variability of both heart and blood pressure measures.

Mulder et al. (1992) showed that initial HR(V) effects disappeared after 10 to 20 min of task performance, while BP remained high and baroreflex sensitivity (BRS) remained low after the initial effects. The authors concluded that these effects were directly related to short-term blood pressure control (baroreflex, Mulder et al., 2009; Van Roon et al., 2004). Baroreceptors monitor changes in blood pressure and influence sympathetic activation and para-sympathetic activation. A continuing elevation of blood pressure increases sensitivity of this system and increases parasympathetic activation and decreases sympathetic activation, lowering heart rate and indirectly blood pressure (Van Roon et al., 2004). Effectively this means that despite ongoing mental effort the increase in blood pressure is reduced and the effects in heart rate and HRV are opposite to the initial effects of the mental workload increase.

So, cardiovascular responses to increased mental workload are often a combination of the described defence reaction, followed by a compensatory response of the short-term blood pressure control system. Whether this combination of effects results in a (further) increase or a decrease in blood pressure depends on the task demands and the possibilities for the operator to regulate workload. Either a continuing rise in heart rate (initial reaction) or a decrease in heart rate (regulation effect) may occur as a result of effort investment, depending on the momentary balance between the defence reaction and the baroreflex control. The combination of these two effects may largely explain the mixed results on heart rate and heart rate variability measures that are found in some studies on prolonged workload in real-world or simulated work situations (Veltman and Gaillard, 1996; Sirevaag et al., 1993; Mulder, 1992; Wilson, 1992; Jorna, 1992; Porges and Byrne, 1992).

After making the distinction between short-term defence response effects and slower effects of the baroreflex, we introduced a short-term analysis approach using cardiovascular measures to improve workload estimation (Stuiver et al., 2012). The results of this study show that by analysing shorter segments of cardiovascular data the difficulties arising when long-term effects come into play can be avoided and measures more sensitive to current workload and less to compensatory processes can be created.

Of course, this knowledge of differential effects on mental effort for short-term and long(er)-term cardiovascular measures is not completely new. In a literature review, Kramer (1991) reported on the sensitivity of heart rate variability to brief periods of workload, and summarized the results of two research groups and concluded that heart rate variability responds within seconds to changes in workload (Aasman et al., 1987; Coles and Sirevaag, 1987). Similarly, Hoover et al. (2011) showed that short-lasting changes on task level could be detected in heart rate variability data by using a short-segment (1 to 2 min) approach. The approach presented in the present study is based on a short-term analysis method successfully applied by de Rivecourt et al. (2008) in simulated flight and a similar approach taken by De Waard et al. (2008) in a driving simulator. The importance of their work for this paper lies in their focus on momentary changes and short-term reactions to task load increases. They showed that an analysis period for heart rate and heart rate variability of 30 s already provides sufficient information to give stable and sensitive results, given that a number of repetitions of such task load increasing events are available. The effectiveness of the short-term approach is based on the knowledge that cardiovascular reactions to temporary increases in task demands are only marginally affected by the long-term compensatory effects of the baroreflex while being sensitive enough to changes in task load. The compensatory influence of the baroreflex on a short time scale (30 to 40 s for example) may be present but is relatively small, as shown by van Roon et al. (2004) using the mentioned baroreflex simulation model.

The main research question of the current study was whether the short-lasting changes in mental effort expected due to additional task demands during driving could be detected in short-segment cardiovascular data, using heart rate, blood pressure and its variability measures. In an experimental study, participants drove on a three-lane motorway and were asked to repeatedly switch lanes as commanded by a simulated navigation system. Mental workload was varied by periodic changes in traffic density and by implementing short periods (40 s) of fog. In the high traffic density periods participants need to process more visual input on which they could base their actions. The cars were also driving much closer to the participants' car and were overtaking more often, requiring more control from the participant. It is therefore expected that in the high traffic density situation more perceptual, central and motor processing is required. The general traffic situation between fog and no fog is not so different, which means that the real difference between conditions is visibility. This suggests at first sight only a difference in perceptual processing resources, but the additional effect of having only a minimum of time to react to unexpected driving situations (i.e. behaviour of other drivers is less visible) during lane-switching might be more important in terms of work load and related information processing.

Based on the findings in previous driving research and the results from literature described above, clear decreases in heart rate variability and systolic blood pressure variability measures as a response to a short lasting increase of workload (both traffic density and fog) are expected, potentially accompanied by small increases in heart rate and blood pressure.

2. Methods

2.1. Participants

Fifteen participants completed six experimental sessions. All of them were students aged between 20 and 25; eight were female. They were required to have their driving licence for at least a year and were required to have driven at least 5000 km in their lifetimes. At the start of the first session of the experiment they filled in a general demographic questionnaire and signed an informed consent. For participation they received a financial reward. The study was approved by the ethical committee of the faculty of Behavioural and Social Sciences at the University of Groningen.