CHAPTER 5 – SHORT-TERM CARDIOVASCULAR MEASURES FOR DRIVER SUPPORT

INCREASING SENSITIVITY FOR DETECTING CHANGES IN MENTAL WORKLOAD

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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 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 demands (40 seconds) on heart rate, blood pressure and derived variability measures are applied as indicators of mental effort. Fifteen drivers participated in 6 sessions of 1.5 hours in a driving simulator study. Two traffic density levels (7.5 minute segments) were compared in which short-segments (40 seconds) 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.

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 & 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 of increased heart rate and blood pressure in combination with decreased heart rate variability and blood pressure variability and 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 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 minutes 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 and para-sympathetic activation. A continuing elevation of blood pressure increases sensitivity of this system and increases parasympathetic 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 an (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 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 (one to two minute) 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 and colleagues (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 seconds 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 seconds for example) may be present but is relatively small, as shown by Van Roon and colleagues (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 seconds) 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 workload 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.

**Methods**

**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 license for at least a year and were required to have driven at least 5000 kilometers 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.
Virtual driving environment and driving task
The study was conducted using an ST Software© driving simulator, consisting of a fixed-base vehicle mock-up with a force feedback steering wheel and automatic transmission (Van Winsum and Van Wolffelaar, 1993). The driver was surrounded by three 32-inch diagonal HD plasma screens. Each screen provided a 70° view, leading to a total 210° view. Participants were required to steer only with their dominant hand in order to allow finger blood pressure measurements to be taken from the other hand.

The participants drove for an hour on a specially designed motorway with three lanes in both directions and no entries or exits. Traffic was handled by a traffic generating protocol that also created the quiet and busy traffic conditions, corresponding to low and high periods of workload. Average time headway, the time between vehicles, was 6 seconds in the quiet condition and 0.4 seconds in the busy condition. The number of vehicles on the road in the quiet condition was six, and in the busy condition there were always a total of 35 other cars on the road.

Participants were instructed to drive at a constant speed of 80 km/h. However, due to the required lane switching, the fact that other traffic drove at speeds slightly deviating from the participants’ speed and because of individual differences in speed preferences, participants’ speed would often differ slightly from 80 km/h. To ensure consistency across conditions with different speeds, the traffic generating protocol was made speed dependent. This means that other traffic would be assigned a relative speed in the range of 15 km/h faster or slower than the participants’ speed. Traffic driving much faster than the participant (more than 11 km/h faster) had to drive in the fast (left hand) lane. Other traffic was allowed to drive in all of the lanes.

The main element of the driving task was to switch lanes on the basis of external commands. A device resembling a navigation system was shown on the dashboard to indicate when a lane change was required. This device indicated in which lane the participant was requested to drive by projecting an arrow on one of the three lanes shown on the navigation display. A script randomly selected which of the two other lanes the participant had to switch to and informed the driver by means of this arrow. The time between entering the indicated lane and a new switch instruction was randomly selected by a script, but was always between 7 to 14 seconds. This makes the task resemble the standardized lane-switching task (ISO 26022, see also Spiessl and Hussmann, 2011). However, the focus in the standardized lane change task lies on the workload of a secondary task and not on the workload of driving itself.

Participants were told to obey standard European traffic regulations. Since the speed of other traffic differed slightly from the speed of the participant, some of the other cars would overtake the participant’s car, while others had to be overtaken. The participants were only allowed to overtake at the left hand side, but were told that other road users could potentially overtake on both sides of the
participant’s car. This means participants had to pay attention both to the left and the right when switching lanes.

Cardiovascular measures
The electrocardiogram (ECG) was recorded using three Ag-AgCl electrodes. The common electrode was placed at the sternum and the other two electrodes on the right and left side of the chest between the two lowest ribs. Blood pressure was measured with a FIN.A.PRES device (Finometer), using the build-in servo-adjust mechanisms to prevent drift in the measured blood pressure levels. Both ECG and blood pressure were recorded at a sampling rate of 250 Hz. Individual heart beats (R-peaks) were detected online from the ECG using an ECG-trigger integrated into a TMS Porti system (Twente Medical System International). Interbeat interval times (IBI) were derived by taking the time between two succeeding R-peaks. The resulting IBI data was automatically corrected using CARSPAN (Mulder, 1992), followed by a visual inspection to check the corrected result.

Mean values of heart rate and systolic blood pressure were calculated using a moving 30-second time window, shifted in time by one-second increments. Resulting in measures calculated on a second by second basis by taking the mean of data segments from 15 seconds before to 15 seconds after each time point (Stuiver and Mulder, 2009). This method resulted in derived variables (profiles) of heart rate and systolic blood pressure as a function of time that have values for every second of the drive.

Heart rate variability and systolic blood pressure variability were computed as spectral values from heart rate and systolic blood pressure in two often used frequency regions. The first ranges from 0.07 Hz to 0.14 Hz (the mid frequency band) and the second ranges from 0.15 Hz to 0.40 Hz (the high frequency band). Similar to the procedure of calculating the mean values described above, new variables (profiles) of heart rate variability and systolic blood pressure variability as a function of time were derived on a second by second basis by calculating spectral values in time segments of 30 seconds as above (Stuiver and Mulder, 2009). Both heart rate variability and systolic blood pressure variability were calculated by normalizing to the mean, called squared modulation index (Veldman et al., 1998). These variables were also logarithmically transformed which results in normally distributed variables (Van Roon et al., 2004). Spectral analysis was performed with CARSPAN (Mulder, 1992).

Blood pressure has not been measured often in driving situations. This is not surprising since available techniques such as the finapres method (Finapres Medical Systems), measuring blood pressure at the finger, are somewhat restrictive in normal driving. This is because these techniques require that a hand or arm be kept still while therefore being obviously incompatible with two-handed operation of the vehicle. However, since cardiovascular effects during driving may be better understood with blood pressure data available, we decided to measure blood pressure at the finger, and to accept the practical limitations that this therefore places on the driving performance of the participants. In order to limit this inconvenience participants’ blood pressure was measured at the non-dominant hand, leaving the
dominant arm available for controlling the car, being used to manual-shift cars this posed no problem for the participants.

Data segmentation and variables
Short periods with increased task demands, as a result of reduced visibility due to fog, were compared to the periods directly preceding the fog. This was done in both the condition with quiet and with busy traffic. A value for the period before the fog was calculated as an average from the profile data directly prior to the period with fog (30 to 10 seconds before the onset of fog). The value for the period during fog was calculated as an average from the profile data during the task load increase (0 to 20 seconds from the onset of fog).

The difference between the values from the periods with and without fog can then be examined, and is taken as a measure for how much the driver responds to the increased task demands. By taking the averages of these values within one session across multiple occurrences of fog, the reliability of the measure is improved. This resulted in two pairs of values within a session: one fog/no-fog pair for high and one for low traffic density. Task load effects on effort investment were then investigated by testing the interaction effect of traffic density condition and the fog/no fog period values.

Analyses on the following cardiovascular variables are reported: mean heart rate (in beats/minute), systolic finger blood pressure (in mmHg), and heart rate variability values and systolic blood pressure variability values from the mid- and high-frequency bands (in natural log-transformed squared modulation index values).

Subjective measures
At eight times during each drive the participants were asked to indicate their experienced mental effort in the last 30 seconds. To do so the participants verbally reported the effort in the last 30 seconds using the Rating Scale for Mental Effort (RSME, Zijlstra, 1993). A large hard copy of the scale was positioned just above the central plasma screen and either just before or at the end of a fog period a beep was played to indicate to the participants that they had to provide (vocally) a mental effort rating.

Experimental procedure
Each participant completed six 1.5-hour experimental sessions. A design with multiple sessions for one participant was chosen to be able to study within and between session effects within participants. The results of the latter are, however, not reported in this paper.

The first session started with a questionnaire, followed by a training ride of ten minutes to get acquainted with the driving simulator. Each of the next sessions, all of which were completed within 3 weeks, started with a shorter training ride of 3 minutes, meant only to let the participant get settled in
the driving simulator. The training rides were then followed by a five-minute baseline (rest) measurement, and then after the rest measurement participants drove under the experimental conditions described in section 2.2 above for exactly an hour per session.

During the drive, the traffic density conditions changed every 7.5 minutes from quiet to very busy or vice versa, starting with the quiet condition in each session. Periods of 40 second fog appeared three times during every traffic condition, spread out evenly over the 7.5 minutes. In summary, every session consisted of three periods of high-density traffic and three periods of low traffic density alternated. In every period fog would appear twice. So a total of twelve times fog appeared in a session, six in high traffic density situations and six in low traffic density situations. The subjective rating on RSME was collected once every 7.5 minutes, timed with one of the four situations (high density/fog, high density/no-fog, low density/fog, low density/no-fog).

Statistical analysis
General Linear Model Repeated Measures tests (SPSS) were used to analyse the data. Repeated Measures MANOVAs were run with two factors: fog/no fog (two levels) and low/high traffic density (two levels). Alpha was set to 5% for all tests, bonferroni corrected post hoc tests were applied when interactions were found and are reported in the result section.

Results

Systolic blood pressure and systolic blood pressure variability
An interaction effect of traffic density and fog (F(1,89) = 13.42, p < .05, ηp2 = 0.489) was found for systolic blood pressure (Figure 11a), indicating that blood pressure increased with the appearance of fog in the high traffic density condition. Statistical tests showed a main effect of traffic density (F(1, 89) = 13.16, p < .05, ηp 2 = 0.485), post hoc tests showed this effect was present before the fog (M = 1.61, SE = .51, p < .05) and also during the fog (M = 2.03, SE = .50, p <.001). It must be noted that the absolute differences in systolic blood pressure with respect to the appearance of fog were actually very small.

Interaction effects of traffic and fog were found for both the mid (F(1,89) = 6.88, p < .05, ηp 2 = 0.329) and high frequency bands (F(1,89) = 10.33, p < .05, ηp 2 = 0.425), of systolic blood pressure variability indicating a decrease of these measures during fog in the low traffic condition (Figure 11b/c), which were not present during the high traffic condition. Statistical analysis further showed a main effect of traffic density for systolic blood pressure variability in both the mid (F(1, 89) = 4.74, p < .05, ηp 2 = 0.253) and the high frequency band (F(1, 89) = 7.34, p < .05, ηp 2 = 0.344). Post hoc tests showed that these main effects can be explained by the differences found in the period without fog in both the mid
(M = 0.106, SE = .033, p <.05) and the high (M = 0.96, SE = .031, p <.05) frequency band. Post-hoc tests showed no effects of traffic density during fog for systolic blood pressure variability (mid or high).

**Heart rate and heart rate variability**

An interaction effect of traffic condition and fog was found for the high frequency band of heart rate variability (F(1, 89) = 4.98, p <.05, ηp² = 0.263), indicating a decrease of HRV with fog in the low workload condition, which was not present in the high workload condition (Figure 12c). Heart rate variability in the mid frequency band (Figure 12b) showed a similar pattern as in the high frequency band without, however, leading to statistical significance. A main effect (F(1, 89) = 6.41, p < .05, ηp² = 0.314) of fog was found in the high frequency band of heart rate variability; post hoc tests showed that variability was only lower during fog in the low traffic density condition (M = 0.066, SE = .024 p <.05). Post hoc tests for fog showed no effects in the high traffic density condition. There were no effects of either fog or traffic density on heart rate.

**Subjective effort**

In addition to the cardiovascular effects mentioned above, a main effect of traffic was also found for subjective effort. Participants reported higher invested mental effort (41.8) on average during high traffic density conditions (F(1, 89) = 77.55, p < .001, ηp² = 0.466) than during low traffic density conditions (31.6). No main or interaction effects of a temporary increase in task demands due to fog were found in ratings of subjective effort.
Figure 11: Values before the appearance of fog and during fog in low and high traffic density conditions. SBP = Systolic blood pressure in millimeters Mercury (mmHg). SBPV mid/high = Systolic blood pressure variability (mid/high frequency band) in natural log-transformed squared modulation index values.
Figure 12: Values before the appearance of fog and during fog in low and high traffic density conditions. HR = Heart rate in beats per minute (bpm). HRV mid/high = Heart rate variability (mid/high frequency band) in natural log-transformed squared modulation index values.
Discussion

Mental effort in fog and traffic conditions

The main purpose of this paper was to investigate whether the sensitivity of cardiovascular measures derived from relative short time segments (30-40 sec) is adequate to detect short-lasting changes in mental effort during driving as a response to an increase in workload. To create changes in mental effort, task demands were increased during normal driving in a lane-switching task by manipulating traffic density (high/low) and introducing short periods of fog (duration 40 seconds). For each cardiovascular variable a reference value calculated from a short period just preceding the fog was compared with a value calculated from the period during the fog.

Two patterns can be distinguished in the data. Firstly, there was a clear decrease in heart rate variability and systolic blood pressure variability as a response to short lasting increases of workload due to fog. This decrease was stronger in the low traffic condition. Secondly, the variability levels of blood pressure and heart rate are lower in the high traffic condition than in the low traffic condition, although this effect only reaches significance in the blood pressure variability measures. Additionally, blood pressure level is somewhat higher in the high traffic condition compared to the low traffic condition. Both types of pattern (for fog and traffic conditions) are indications of increased effort during short periods of increased workload. The effects of traffic density are confirmed by the subjective reports given by the participants. A clear effect of increased traffic density can be seen in the results of these measures. There was no difference found, however, for the subjectively reported effort for driving during the periods of fog. This seems contrary to the results found in the cardiovascular measures, but is in line with other research that has used fog to manipulate task demands but failed to find subjective results (Van der Hulst, 1999; de Waard et al., 2008).

The largest cardiovascular effects of fog were found in the low traffic condition: lower values both for heart rate variability and for blood pressure variability measures. This effort effect could be expected since in the high traffic density condition perception, central and motor control processing can be assumed to be higher. It is remarkable, however, that the effects of fog are larger than those of the traffic condition. Our interpretation is that during the high traffic condition as well as during the low traffic with fog, mental load is quite high, resulting in a ceiling effect for these variability measures and for heart rate. Only during the low traffic, no fog condition the required mental effort is at a lower level that can be distinguished from the other conditions by this set of variables. These findings may also contribute to an explanation for the non-significance of some of the expected effects, in particular for HRV in the mid frequency band and heart rate. The difference in task load between conditions was quite subtle: two similar driving conditions were compared, not a driving condition compared to rest.
This corresponds largely to findings of other researchers (Jorna, 1992; Roscoe, 1992; Wilson, 1992) who stressed the limitations of the sensitivity of heart rate variability measures at this level, while both Aasman et al. (1987) and Veltman & Gaillard (1998) have shown the sensitivity of HRV for different task load levels, as well as demonstrating its limitations in situations of extreme effort investment. This pattern of effects, the response to a task load increase (fog) starting in a low task load situation as well as the absence of a response in periods of already high task demands, is therefore quite informative of the subjects’ state during task performance.

So, assuming the smaller reaction in the difficult task condition indicates a ceiling effect, this information can potentially be used as input for an adaptive system that tracks how operators cope with the current situation to adjust workload to the right level. However, to be able to do that we first need to better understand what this ceiling effect exactly means in terms of performance degradation and how it can be used to regulate workload.

**Using short-term measures**

In the introduction we mentioned possible problems with heart rate and blood pressure variability measures as indicators of changes in mental effort in a setting with long-lasting task performance (Veltman and Gaillard, 1996; Sirevaag et al., 1993; Wilson, 1992; Jorna, 1992; Mulder et al., 2009). These were related to compensatory effects of the blood pressure control system (baroreflex), resulting in decreased (or less increased) blood pressure levels in combination with decreased (or less increased) heart rate and higher variability levels of heart rate and blood pressure. Immediate effects of increased effort can be ascribed to activation of the sympathetic system in combination with vagal inhibition (Van Roon, 2004; Berntson et al., 1994; Boucsein & Backs, 2000), whereas the compensatory mechanism of the baroreflex are associated with increased para-sympathetic activation (‘recovery’) and reduction of sympathetic activation. Therefore the workload effects on heart rate (variability) may be diminished or even cancelled when looking at longer periods.

The approach proposed in this paper makes it possible to study current and immediate effects of workload changes using short-segment analysis of cardiovascular (variability) measures in corresponding periods of increased workload. Moreover, the results are to a large extent in line with earlier findings in our group during simulated mental work, using either driving, flying or planning activities (De Waard et al., 2008; De Rivecourt, 2008; Stuiver et al, 2012).

**Limitations**

One of the limitations of this study is the fixed order of traffic conditions, which limits the interpretation of the cardiovascular results in terms of traffic intensity. In particular, there is a large
chance that effects of heart rate variability are reduced markedly by this fixed order of traffic conditions. On the other hand, the absence of this effect underlines the relevance of the short-term approach: short-lasting fog effects can be better detected than longer lasting traffic effects.

Other restrictions are the small age range of our participants and the lack of insight the presented data give in possible (individual) adaptive regulation processes of the baroreflex, which still may reduce some of the reported effects.

To be able to properly measure blood pressure while driving, participants were required to steer with only one hand, while wearing a cuff on a finger of the other hand, which had to remain relatively still. Since the task consisted only of switching lanes it required little physical effort, reflected in the fact that none of the participants seemed to have trouble performing the lane changes.

**Conclusions**

A major benefit of this short-term analysis approach is that the recorded cardiovascular measures were relatively unaffected by the compensatory effects of the short-term blood pressure regulation system. This enables the possibility to distinguish low effort conditions (low traffic, no fog) from the other more effortful task conditions. A relevant finding is that the largest effects of workload manipulation by fog were found in the conditions with low traffic intensity, indicating a kind of ceiling effect on variability measures. We think that this finding gives an opportunity for detecting state dependent effort changes, a result that is promising for the development of adaptive driver support systems. Based on the present findings, this approach improves sensitivity to workload changes and further improves diagnosticity of workload measures as well, while being less sensitive to compensatory blood pressure control effects.

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