Physiological correlates of mental effort as manipulated through lane width during simulated driving

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***Abstract*—Previous studies suggest that physiological effects of mental effort as manipulated trough cognitive task difficulty differ from effects of mental effort as manipulated trough a visuomotor task such as lane keeping in simulated driving. Most notably, heart rate increases with mental effort in the former but not in the latter task. EEG seems to be indicative of mental effort in both cases. In previous research [1], Brouwer and colleagues examined effects of mental effort as manipulated in a cognitive (memory) task on a range of physiological signals. In the present research we examine the same types of physiological signals using the same kind of analysis in a visuomotor (simulated driving) task. In this case, mental effort was manipulated using wide and narrow lanes. Effects of task difficulty on both subjective mental effort and behavioral variables were comparable across tasks. Effect of task difficulty was replicated for respiration frequency and to some extent for EEG alpha activity. However, in contrast to the cognitive task [1], skin conductance and heart rate related variables were not significantly affected by task difficulty in the current visuomotor task. We argue that differences in visual attention and cerebral energy demand between the types of tasks may be at the basis of this.**

Keywords—driving; mental effort; workload; stress; arousal; EEG; physiology; heart rate; HRV; skin conductance; respiration

I. INTRODUCTION

Continuous information about a user's level of workload or mental effort would be valuable in a range of situations. It could be used to build systems that adapt themselves to the user in real time: adaptive automation [2]. For instance, certain tasks could be automated when workload gets too high, or an incoming telephone call could be withheld. Also, this information could be used to evaluate working with different systems in a continuous manner, comparing fluctuating mental effort between systems or identifying points of improvement. While behavioral performance can be used as an indicator of mental effort, performance variables are usually not continuously available. In addition, they do not exactly map on mental effort. For example, a user can increase mental effort when a task gets more difficult, therewith keeping performance at the same level while mental effort has actually increased. Also, performance can change due to change in mental effort and/or chance in other task related factors. Subjective measures can be used to gauge workload or effort, but they are not continuously available as well. Users can be asked to indicate their experience repeatedly, therewith giving a more continuous measure, but this comes at the cost of an extra task for the user and distraction of the main task. Similar to performance variables, subjective measures cannot always be taken at face value, especially if users can be expected to be under (social) pressure to provide certain answers or if subjective reports refer to experiences some time in the past [3].

Previous research has shown effects of workload or mental effort on a range of physiological variables. Mental effort has usually been experimentally varied through cognitive task difficulty using double tasks (e.g. [4]) or varying memory load (e.g. [5]). Even though at least part of the effects as found in many of these studies could be due to confounds (discussed in [6]), qualitatively similar effects have been found in well-controlled studies varying cognitive task difficulty [1], [7], notably an increase of heart rate and skin conductance with increasing mental effort or task difficculty. Another (well-controlled) set of studies used incentive (financial or otherwise) to manipulate mental effort (e.g. [8], [9]). These studies report qualitatively similar effects as well.

Even though the studies cited above suggest a more or less coherent picture of the physiological effects of mental effort, no or only weak effects have been found when mental effort varied due to effects of physical state such as fatigue ('compensatory effort' – [10]) and increasing skills through learning ([1]). While various reasons could be responsible for this ([1],[10]), it is clear that we cannot always generalize effects of mental effort as understood psychologically to physiological variables. As comprehensively discussed by Fairclough [11], the relationship between physiological measures and psychological meaning is complex. One of the issues is that psychological states like mental effort may vary on its own or may be associated with variations in affective states such as an aversive experience associated with tension [12]. Reconceptualization of psychological and physiological processes may be required to design better models of the relation between mental states (psychological elements) and physiology [13], [6].

In the present study, we want to examine physiological effects of increasing effort due to increasing task difficulty that is visuomotor rather than cognitive in nature, and not caused by adding extra tasks in order to avoid having to deal with prioritizing strategies.

Such studies have been performed before by Dijksterhuis, Stuiver and colleagues. Dijksterhuis et al. [14] examined drivers' physiology in a simple simulated lane keeping task while manipulating mental effort through driving speed. They report successful visuomotor workload classification using EEG, but did not find effects on EOG and cardiovascular variables (personal communication). In [15], Dijksterhuis et al. keep driving speed fixed, and varied lane width and traffic density while examining heart rate, hart rate variability and respiration. There was no effect of lane width on any of these three variables. However, this could be explained by the fact that the effect of lane width on subjectively experienced mental effort was, though significant, relatively small in terms of scores on the Rating Scale Mental Effort (a difference of 20 points on the RSME scale for high traffic density and a substantially smaller difference for low traffic density). Effects of traffic density, a manipulation that is arguably less visuomotor in nature, were not only found on subjectively rated subjective effort, but also on physiological variables (a small decrease in heart rate and a decrease in heart rate variability). Stuiver and Mulder [16] recorded ECG and blood pressure during simulated driving. Traffic density and viewing conditions (fog) were varied. There were no effects on heart rate, but in the easiest condition (no fog, low traffic density) high frequency heart rate variability was higher than in the other conditions. Interaction effects were also observed for blood pressure.

In sum, these studies suggest that workload as varied through visuomotor difficulty may cause less clear effects on peripheral physiology than workload as varied through cognitive task difficulty, while neurophysiological signals (EEG) may be sensitive for this kind of workload as well. In order to examine this more closely, we induced similar subjective mental effort scores for a low and high workload visuomotor task as we obtained in our previous study on cognitive workload [1]. We examine the same, relatively large, range of physiological variables using the same kind of analysis as in [1]. This will allow for a rough comparison between physiological effects of varying levels of cognitive and visuomotor workload.

II. Methods

A. *Participants*

17 participants (6 female), recruited through the participant pool of TNO, completed the experiment. When recruiting participants, we excluded individuals wearing glasses, using psychopharmaca and suffering from simulator sickness, cardiovascular diseases, diabetes and neurological disorders based on self-report. They were between 18 and 36 years old (M = 24.7; SD = 5.8). Participants received a monetary reward to make up for their travel and time. The study was approved of by the local ethics committee. All participants signed an informed consent form prior to taking part in the experiment.

B. *Materials*

Stimulus environment: Participants drove a simple driver simulator consisting of a force feedback Logitech steering wheel, a Playseat car seat, pedals (that were only used to start driving – driving speed was fixed throughout the experiment) and a 30” screen depicting the environment. The environment was programmed using OpenSceneGraph 3.0.1. It consisted of a clouded sky, a flat green environment and a straight road with lines at the sides. The experimental road was divided in 10 equal road segments. Each road segment was split such that the first three minutes, participants drove a wide lane, and the following five minutes participants drove a narrow lane. Thus, the experiment always started with a wide lane (3.5m). Lane width of the narrow lane was fixed per participant but depended on his or her performance. It was 2.5m for four participants, 2.6m for three, 2.7m for five, and 2.8m for five participants. A wind simulation model was superimposed on the steering wheel such that the participants were obliged to continuously make small steering adaptations. When participants crossed the lines, a rumble was presented through a sub woofer of a 5.1 audio system for as long as they remained across the lines.

Subjective measures: We used two scales to gauge participants' mental state at the time just before the experimental ride and right after. The Karolinska Sleepiness Scale (going from 1 ‘extremely alert’ to 9 ‘very sleepy, great effort to keep alert, fighting sleep’ [17]), and a Visual Analogue Scale regarding relaxation. In this VAS participants drew a vertical line on a 10-cm horizontal line were the extreme left side was denoted as ‘very relaxed’ and the extreme right side as ‘very tensed’. In addition, participants filled out a Rating Scale Mental Effort (going from 0 to 150 where 3 is labeled as ‘Not at all effortful’ and 115 is labelled as ‘tremendously effortful’ – [18]). The RSME was filled out to indicate mental effort spent for the experimental ride as a whole, for driving the wide lanes, and for driving the narrow lanes.

Physiological measures: EEG, EOG, ECG, skin conductance and respiration were recorded using a Biosemi ActiveTwoMk II system, with a sampling frequency of 512 Hz. For EEG, 32 active silver-chloride electrodes were placed according to the 10-20 system. For EOG, 4 electrodes were fitted to the outer canthi of both eyes, as well as above and below the left eye. ECG electrodes were placed on the right clavicle and on the lowest floating left rib. Skin conductance was measured by placing gelled electrodes on the fingertips of the index finger and the middle finger of the non-dominant hand. Chest respiration was recorded using a Biosemi respiration band placed at the height of the lower side of the sternum. Pupil size was recorded using a Tobii x50 eye tracker, sampling at 50 Hz. EOG and pupil size data have not been analyzed yet.

C. Procedure

Participants were explained about the procedure and filled out the informed consent form. We asked them to drive without crossing the lines. They were informed that there would be no other traffic and that the road was one way so that it would be good to drive in the middle of the road. Participants started a practice ride on a straight road for 5 minutes. We encouraged them to cross the lines on purpose to experience the rumble. Then participants drove for 18 minutes on a road that changed width every two minutes: three times each of the three widths 2.2, 2.3 and 2.4m. The order of lane widths was such that each lane width was presented once in the beginning, middle and end and that there was a change every two minutes. We asked them to try and not cross the lines. The experiment leader monitored performance, noted number of line crossing errors per lane segment and determined lane width of the narrow lane in the experimental part for each participant individually. The purpose of this was to achieve a more equal error rate across participants compared to taking a fixed narrow lane width. After the practice rides, participants had a short break and were fitted with the sensors. They were seated in the simulator again, and filled out a general questionnaire on driving experience, physical exercise, and the use of alcohol, tobacco, and coffee. They then rated their present experience on the VAS and the KSS. Then the 80 minutes experimental ride started. Participants were asked not to talk, to move as little as possible and to not apply pressure on the skin conductance electrodes. Every time the lane width changed, the number of changes so far was displayed, so that participants knew how far they advanced with the experiment. Immediately following the end of the experimental drive, participants again indicated their present experience by filling out the VAS and the KSS. They also filled out the RSMEs and they were asked about what they thought was causing line crossing errors (such as inattention or sleepiness) and how bad they felt about making an error (not analyzed here).

D. Analysis

For each participant, each of the two lane widths and each of the 10 lane width repetitions (road segments), we determined the value of a range of dependent variables to measure task performance and physiology as specified below.

An error was defined as crossing a line and returning again. We determined number of errors per minute and the mean error duration.

EEG data were filtered by a 0.05 Hz high pass and a 65 Hz low pass filter. EEG measures that we examined here are power in the alpha band at Pz and power in the theta band at Fz. Power was determined in frequency bands of interest across intervals of 2500 ms. Intervals for which the standard deviation of EEG traces exceeded 15 μV were excluded from analysis which was 3.5% of the data for Pz and 7.0% for Fz mostly due to two participants (where excluding them did not change the observed patterns in the data). For Pz, power was determined in frequency bands from 8 to 13 Hz after which the power as found in that epoch was natural log transformed. For Fz, theta power was determined in frequency bands from 4 to 8 Hz and natural log transformed. For each participant, each of the two lane widths and each of the 10 lane width repetitions, log powers were then averaged across epochs.

The skin conductance signal was filtered by a 0.001 Hz high pass and a 30 Hz low pass filter. The mean skin conductance level was determined by averaging skin conductance for each wide and narrow road segment. Skin conductance measurement failed for one participant who is left out of the skin conductance analysis.

The ECG signal was filtered by a 15 Hz high pass and a 35 Hz low pass filter. As a measure of heart rate, we determined the median RRI for each wide and narrow road segment. RRI is the interval between successive heart beats or more precisely, the interval between subsequent R-peaks in the ECG. Based on the RRIs, three measures of heart rate variability were computed. The root mean squared successive difference (RMSSD: [19]) between the RRIs reflects heart rate variability. Heart rate variability was also computed as the natural log transformed power in the high (0.15–0.5 Hz) and mid (0.07-0.15 Hz) frequency range of the RRI over time using Welch's method [20] as implemented in Matlab.

The respiration signal was filtered by a 0.1 Hz high pass and a 5 Hz low pass filter. Breathing frequency was defined as the median time interval between the peaks where intervals corresponding to a higher breathing frequency of 30 and a lower breathing frequency than 2 breaths per minute were removed (3.7% of the intervals).

Repeated measures ANOVAs were conducted on each variable with factors lane width (wide and narrow) and road segment (1 through 10). A variable's sensitivity to effort as induced by varying lane width should be reflected by a main effect of lane width. An effect of a factor co-varying with time should be reflected by a main effect of repetition. Paired t-test were applied where appropriate.

III. Results

A. Subjective measures

The experimental driving task as a whole was rated with a mean RSME of 64.2. The wide lane was rated with a score of 37.9 (close to 'somewhat effortful') and the narrow lane with a score of 80.2 (close to 'very effortful'). The difference was significant (t_{16}=6.08, p=<0.01). Participants did not indicate a subjective difference in feeling relaxed or tensed before compared to after driving (VAS score 2.9 before and 2.8 after driving; t_{16}=0.21; p=0.84). They did indicate to feel more sleepy after compared to before driving (KSS score 4.9 before and 6.6 after driving, i.e. roughly going from 'Neither alert, nor sleepy' to 'Sleepy, but no effort to keep alert'; $t_{16}=-2.97$; $p<0.01$).

B. Behavioural performance

The first two rows of Table 1 shows the results of the repeated measures ANOVAs on the behavioural measures. The top left graph in Fig. 1 shows the mean number of errors per minute for each wide and narrow road segment. Clearly, participants make more errors in the narrow than the wide lanes ($F_{1,16}=41.61$; $p<0.01$) and there is an effect of road segment ($F_{9,144}=5.31$; $p<0.01$) where number of errors rapidly increase over time. The number of errors seem to decrease again at the end, but still, the number of errors during the last wide and narrow road segment is larger than during the first road segment as indicated by a paired t-test ($t_{16}=2.58$; $p=0.02$). There is also an interaction between road segment and lane width ($F_{9,144}=2.03$; $p=0.04$). Mean error duration (top left graph in Fig. 1) reflects the same pattern as the number of errors per minute, with longer error duration for narrow than wide lanes ($F_{1,16}=18.48$; $p<0.01$) and an effect of road segment ($F_{9,144}=4.15$; $p<0.01$) where error duration seems to rapidly increase at the beginning followed by small decrease.

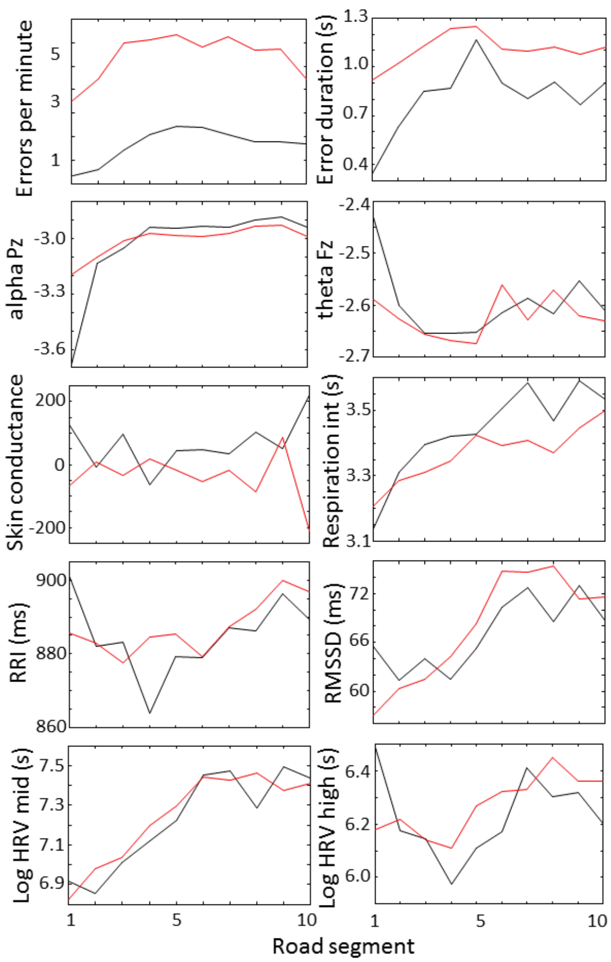

Fig. 1. Different variables averaged over particpants for each road segment and each lane width seperately. Red traces represent narrow lanes, black traces wide lanes.

TABLE I. RESULTS OF REPEATED MEASURES ANOVAS (P-VALUES). P-VALUES<0.05 ARE PRINTED IN BOLD

	Lane width	Road segment	Interaction
Errors per minute	**<0.01**	**<0.01**	**0.04**
Mean error duration	**<0.01**	**<0.01**	0.18
EEG alpha Pz	**0.03**	**<0.01**	**0.01**
EEG theta Fz	**<0.01**	**<0.01**	**<0.01**
Mean skin conductance	0.10	0.83	**0.04**
Respiration interval	**<0.01**	**<0.01**	0.40
RRI median	0.46	**0.04**	0.10
HRV: RMSSD	0.45	**0.04**	0.28
HRV: mid frequency	0.59	**<0.01**	0.75
HRV: high frequency	0.27	0.20	0.14

C. Physiology

Rows 3-10 of Table 1 show the results of the repeated measures ANOVAs on the physiological measures. The lower eight graphs in Fig. 1 shows the different physiological measures for each wide and narrow road segment.

We found an effect of lane width on alpha activity at Pz, where alpha was weaker rather than stronger for wide than narrow lanes. However, there was a strong interaction with time indicating that this effect is due to the very first blocks. Similarly, for theta the effect of lane width, that is in the other direction than expected, seems to be due only to the first road segments.

No systematic effect of time or lane width was observed on skin conductance level. Skin conductance tended to be lower during narrow compared to wide lanes, especially during the last road segments (significant interaction between lane width and time).

Respiration intervals were shorter, i.e. respiration frequency was higher, for the narrow compared to the wide lanes. There was also a clear effect of time where respiration interval increased (i.e. frequency decreased) over time.

None of the ECG-related variables showed an effect involving lane width. There was an effect of time on RRI, where RRI was longer (heart rate lower) towards the end (and at the beginning) of the drive. An effect of time on RMSSD and mid-frequency HRV indicated that HRV increased over time during the first half of the drive after which a plateau was reached.

Table 2 summarizes the results of the present study, manipulating mental effort through a visuomotor task, and the results of Brouwer et al. [1] where mental effort was manipulated through a cognitive (n-back) task.

IV. DISCUSSION

The effect of task difficulty on subjective mental effort was similar in both the present and the n-back study: participants who performed the visuomotor task rated driving narrow and wide lanes with RSME scores of 38 and 64 respectively (a difference score of 26); participants who performed the n-back

TABLE II. EFFECTS OF DIFFICULTY, TIME AND INTERACTIONS COMPARED ACROSS THE PRESENT AND PREVIOUS STUDY AS INDICATED BY EFFECT SIZES (NS MEANS NO SIGNIFICANT EFFECT). BOLD TEXT INDICATES SIGNIFICANT EFFECTS IN THE PRESENT STUDY THAT ARE SIMILAR AS FOUND IN THE N-BACK STUDY

	N-back (Brouwer et al., 2014)			Lane width (current study)		
	difficulty	time	interaction	difficulty	time	interaction
Behavioural performance *(errors and reactiontime; errors and errorduration)*	0.55 0.58 worse for difficult	0.22 0.21 improving	0.07 0.12	**0.72** **0.54** **worse for difficult**	0.25 0.21 deteriorating	0.11 NS-0.07
EEG alpha Pz	0.27 lower for difficult	0.12 increasing	0.06 Increase more strongly for easy task	**0.25** **initially higher for difficult, but later blocks as expected**	**0.60** **increasing**	**0.63** **increase more strongly for easy task**
EEG theta Fz	NS-0.01	NS-0.04	NS-0.04	0.36 Lower for difficult, no effect in later blocks	0.16	0.15 effect of lane width due to the first blocks
Mean skin conductance	0.12 higher for difficult	NS-0.05	NS-0.04	NS-0.17 trend: lower for difficult	NS-0.04	0.12
Respiration interval	0.41 lower for difficult	NS-0.06	NS-0.03	**0.51** **lower for difficult**	0.23 increasing	NS-0.06
RRI median	0.32 lower for difficult	0.48 increasing	NS-0.06	NS-0.03	0.11 U-shape	NS-0.10
HRV: RMSSD	0.21 lower for difficult	0.19 increasing	NS-0.03	NS-0.04	**0.11** **increasing**	NS-0.07
HRV: mid frequency	NS-0.05	NS-0.06	NS-0.03	NS-0.02	0.30 increasing	NS-0.04
HRV: high frequency	0.15 lower for difficult	0.16 increasing	NS-0.05	NS-0.07	NS-0.08	NS-0.09

task rated the 1-back and the 2-back task with RSME scores of 33 and 57 (a difference score of 24). Effects of task difficulty on behavioral variables were also similar (Table 2). Time related effects differed between the two studies. Whereas participants got better over time in the n-back task (for the difficult task), they rather got worse in the driving task. An explanation for this discrepancy may be the difference in familiarity between the n-back and the lane keeping task. The lane keeping task in the driving simulator is nearly identical to visuomotor coordination necessary during real driving (or bike riding), and is therefore already highly learned. Time related effects will therefore more likely be related to fatigue or boredom rather than learning, while the reverse is true for the unfamiliar n-back (2-back) task.

For respiration frequency, difficulty level in the current and previous study show comparable effects. EEG alpha and theta look similar across studies except for data from the first road segments. The behavioral data suggests that during these first segments participants spent most effort. If we take this to mean that effort starts high and then steeply decreases, the reversed effect could be explained (note that the experiment always started with a wide lane).

Consistent with studies by Dijksterhuis and colleagues [14], [15] we did not find an effect of lane width on RRI and RMSSD while these variables were sensitive to effort as manipulated by n-back difficulty level. Looking at effect sizes and trends, this is not likely due to the smaller number of participants in this experiment. Skin conductance does not show an effect of lane width either (with the trend in the opposite direction as expected), whereas an effect of task difficulty was found in the n-back study.

Why are skin conductance, RRI and RMSSD not sensitive to different difficulty, or mental effort conditions in driving and are sensitive in the n-back task? Possibly, participants may not have spent more effort in narrow compared to wide lanes while they did in 2-back compared to 0-back. RSME scores may have indicated otherwise since they may have been affected by other subjective processes, such as perceived risk that did not play a role in the n-back task. Subjective reports on perceived risk and mental effort have been found to be strongly related in driving studies [15],[21]. Another reason that we proposed at the outset of this study is that the type of effort, and its underlying physiological processes, differed between the visuomotor and the cognitive task. Effects of mental effort on physiological variables are partly due to differences in cerebral energy demand [10], and there may be a larger difference in required cerebral energy demand between the 0-and 2-back task, where the 2-back task is a difficult mental updating and memory task whereas driving a narrow road rather involves 'paying more attention', focusing on the road and correct if deviations of the desired trajectory. Notably, we found a strong effect on heart rate in the n-back task where heart rate increased with task difficulty. In the current visuo-motor study, there was no effect, and Stuiver and Mulder [16] even found the opposite effect of a decreasing heart rate with task difficulty. This is consistent with decreasing heart rate to be associated with increased visual attention [22] [23].

In sum, generalization of physiological correlates of the psychological construct 'mental effort' as it is subjectively reported is difficult. We need to find the true mapping between physiology and psychology, e.g. by subdividing the apparently too broad construct of mental effort into smaller building blocks that may or may not play a role in specific types of mental efforts, such as visual attention, short or long term memory and fine movements [6] [13] or by relating the psychological construct to anticipated action. Alternatively, and for practical applications of physiological correlates of mental state (e.g. in adaptive automation), effects should be carefully studied within their context of use. Finally, a way to deal with the lack of generalization across tasks could be in finding invariants using machine learning [24]. As also indicated by this study, time effects should be taken into account for both practical applications as well as design of experiments [25].

ACKNOWLEDGMENT

Thanks to Martin van Schaik for organizing and recording the participants. Thanks to Ingmar Stel for the simulated driving set-up.

REFERENCES

[1] Brouwer, A.-M., Hogervorst, M. A., Holewijn, M., & van Erp, J.B.F., 2014. "Evidence for effects of task difficulty but not learning on neurophysiological variables associated with effort," International Journal of Psychophysiology 93, 242-252.

[2] Byrne EA, Parasuraman R., 1996. "Psychophysiology and adaptive automation," Biol Psychol. 42(3):249-68.

[3] Nisbett, R. E., & Wilson, T. D., 1977. "Telling more than we can know: Verbal reports on mental processes,". Psychological Review, 84(3), 231-259.

[4] Fairclough, S.H., Venables, L., Tattersall, A., 2005. "The influence of task demand and learning on the psychophysiological response," Int. J. Psychophysiol. 56 (2), 171–184.

[5] Ayaz, H., Shewokis, P.A., Bunce, S., Izzetoglu, K.,Willems, B., Onaral, B., 2012. "Optical brain monitoring for operator training and mental workload assessment," Neuroimage 59 (1), 36–47 (Jan 2).

[6] Gerjets P, Walter C, Rosenstiel W, Bogdan M and Zander TO, 2014. "Cognitive state monitoring and the design of adaptive instruction in digital environments: lessons learned from cognitive workload assessment using a passive brain-computer interface approach," Front. Neurosci. 8:385.

[7] Mehler B, Reimer B & Coughlin JF, 2012. "Sensitivity of physiological measures for detecting systematic variations in cognitive demand from a working memory task: an on-road study across three age groups," Hum Factors, 54(3):396-412.

[8] Ewing, K.C., Fairclough, S.H., 2010. "The effect of an extrinsic incentive on psychophysiological measures of mental effort and motivational disposition when task demand is varied," Proc. Hum. Factors Ergon. Soc. 1, 259–263.

[9] Scher, H., Furedy, J.J., Heslegrave, R.J., 1984. "Phasic T-wave amplitude and heart rate changes as indices of mental effort and task incentive," Psychophysiology 21, 326–333.

[10] Fairclough, S. H., Mulder, L. J. M. Psychophysiological processes of mental effort investment. In Wright, R., Gendolla, G. (Eds), 2012. How motivation affects cardiovascular response: Mechanisms and applications. (pp. 61-76). Washington, DC, US: American Psychological Association, xiv, 424 pp. http://dx.doi.org/10.1037/13090-003

[11] Fairclough, S. H. 2009. "Fundamentals of physiological computing," Interacting with Computers, 21, 133-145.

[12] Hockey, G.R.J., 1997. "Compensatory control in the regulation of human performance under stress and high workload: a cognitive-energetical framework," Biological Psychology 45, 73–93.

[13] Cacioppo, J.T., Tassinary, L.G., 1990. "Inferring psychological significance from physiological signals," American Psychologist, 45, 16-28.

[14] Dijksterhuis C., de Waard D., Brookhuis K.A., Mulder B., de Jong R., 2013. "Classifying visuomotor workload in a driving simulator using subject specific spatial brain patterns," Frontiers in Neuroscience, 7:149.

[15] Dijksterhuis, C., Brookhuis, K.A., & De Waard, D., 2011. "Effects of steering demand on lane keeping behaviour, self-reports, and physiology. A simulator study," Accident Analysis and Prevention, 43, 1074-1081.

[16] Stuiver, A., Mulder, B. 2014. "Cardiovascular state changes in simulated work environments," Front. Neurosci. 8:399.

[17] Akerstedt T, Gillberg M., 1990. "Subjective and objective sleepiness in the active individual," International Journal of Neuroscience, 52, 29–37.

[18] Zijlstra, F.R.H., 1993. Efficiency in work behaviour. A design approach for modern tools. (PhD thesis, Delft University of Technology), Delft University Press, Delft, The Netherlands.

[19] Goedhart, A.D., Van der Sluis, S., Houtveen, J.H., Willemsen, G., De Geus, E.J.C., 2007. "Comparison of time and frequency domains of RSA in ambulatory recordings," Psychophysiology 44, 203–215.

[20] Welch, P.D., 1967. "The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging Over Short, Modified Periodograms," IEEE Transactions on Audio Electroacoustics, AU-15, 70–73.

[21] Lewis-Evans, B., Rothengatter, T., 2009. "Task difficulty, risk, effort and comfort in a simulated driving task—Implications for Risk Allostasis Theory," Accident Analysis & Prevention, 41(5), 1053-1063.

[22] Lacey J.I., Lacey B.C., 1970. Some automatic-central nervous system interrelationships, Physiological Correlates of Emotion, ed P. Black (New York, NY: Academic Press), 205–227.

[23] Brouwer, A.-M., van Wouwe, N., Muehl, C., van Erp, J.B.F., Toet, A., 2013. "Perceiving blocks of emotional pictures and sounds: effects on physiological variables," Frontiers in Human Neuroscience, 7:295, doi: 10.3389/fnhum.2013.00295.

[24] Lemm S, Blankertz B, Dickhaus T, Müller KR, 2011. "Introduction to machine learning for brain imaging," Neuroimage, 56(2):387-99. doi: 10.1016/j.neuroimage.2010.11.004.

[25] Brouwer AM, Zander TO, Van Erp JBJ, Korteling H and Bronkhorst AW, 2015. "Using neurophysiological signals that reflect cognitive or

affective state: Six recommendations to avoid common pitfalls," Front. Neurosci. 9:136. doi: 10.3389/fnins.2015.00136