Physiological-Based Assessment of the Resilience of Training to Stressful Conditions

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Abstract. Russian applied psychophysiology has a wide experience of using the heart rate variability (HRV) measures for the assessment of operator workload. However, 'workload indexes' that have received a wide practical application, such as tension index (TI), are not sensitive to the moment-to-moment changes of operator physiological arousal level during the performance of cognitive tasks. In this connection, a new method of HRV analysis called CS-index is offered. This index permits to identify moment-to-moment changes of operator's functional state. The presented research shows that CS-index is sensitive to task load factors, such as task difficulty level and stressful conditions and allows to differentiate experienced and novice operators during their performance on a simulator. If the CS-index proves to be reliable enough, its combination with the Automated Expert Modeling for Automated Student Evaluation (AEMASE) approach can considerably raise the efficiency of operator training.

Keywords: heart rate variability, cognitive workload, training.

1 Introduction

Russian applied psychophysiology has accumulated a rich experience of using the heart rate variability (HRV) measures for the assessment of operator cognitive and emotional workload during professional activity [2-5, 6]. Physiological hardware-software complexes such as the "Physiologist-M", used as devices to control the success of flight skills development on simulators were already used in the seventies of the XX-th century in pilot training in Russia (USSR). Such complexes were intended for pilot workload assessment ("the physiological cost of performance") at certain stages of the flight (takeoff, landing, fighting application, piloting systems failure etc.) and were based on the number of psychophysiological measures, such as heart rate, respiratory rate, respiratory minute volume, quality of secondary cognitive task performance during the performance of the basic training task [14]. Various methods of HRV analysis were developed. They enable us to assess cognitive and emotional workload level of a human operator during the professional work performance [6, 9, 12, 15].

D.D. Schmorrow et al. (Eds.): Augmented Cognition, HCII 2009, LNAI 5638, pp. 563–571, 2009.

A so-called index of regulatory systems tension by Baevskii (IT) based on the analysis of characteristics of R-R intervals distribution for 3-minutes time intervals has received a wide practical application [4, 5]. The IT growth points at the increasing tone of the sympathetic branch of the autonomic nervous system, which, in turn, shows the level of mobilization of physiological regulation system on the estimated time interval. However, the IT and other similar methods of HRV analysis are not sensitive to moment-to-moment changes of operator physiological arousal level during the performance of cognitive tasks, and this complicates their usage for augmented cognition applications.

In this connection, a new method of HRV analysis called CS-index is offered [7]. This index enables to identify moment-to-moment changes of operator functional state. The approach based on the analysis of “transitive” (unsteady) phases in instantaneous heart rate (IHR) dynamics under cognitive workload intensity change was offered along with it. “Transitive” phase is understood as the period of transition of HR regulation system from one steady state to another. In the instantaneous heart rate dynamics with increased workload intensity a number of consecutive phases can be identifies: “steady-state 1” - an initial state of heart rate regulation, that is observed before the increased workload intensity; “transitive (unsteady) state”- the state of primary mobilization, characterized by IHR increasing, caused by the workload intensity increase; “steady-state 2”- a state of heart rate regulation, characterized by IHR indicators stabilization at a new level. It is indicated that in the course of training reduction of intensity and duration of “transitive” phases in IHR dynamics and decreased physiological cost of adaptation to the workloads is identified among students [11, 13].

2 Study

The purpose of the present research was to empirically assess the ability of various heart rate regulation indicators to identify changes in cognitive activity of novice and experienced operators during their professional tasks performance on simulator.

Participants. A total of 40 participants, 21 experienced train drivers and 19 novice train drivers, aged from 20 to 43 years, took part in this study. The experienced drivers were recruited from locomotive depots. The novice train drivers were recruited from the training centers of the “Russian railways” Public Corporation. The experienced train drivers had a mean train driving experience of 10 years. The novice train drivers had no experience of driving.

Procedure. A medium-fidelity fixed-base train simulator, developed by the company “Spectrum”, Russia, was used in the experiment. Each participant performed six 15-minutes scenarios on a simulator. Train driver activity at the performance of the following professional tasks was simulated in the course of the scenario performance: continuous monitoring of the visual signals appearing from out of cab space, regulation of the locomotive movement speed, speaking with the use of communication device. Scenarios had three complexity levels: low, medium, high, which varied in intensity of perceived road signals and also in speed and characteristics of simulated train movement. Half of scenarios included critical incidents that simulated damages in the locomotive alarm system. The given incidents were connected with sharp increase of perceptive and working memory loads and also required operator multitask under time pressure. Simultaneously with the primary driving task participants performed a secondary sensory-motor task: they responded to visual signals appearing on the bottom of the simulator display with the frequency of 1 time in 10 seconds.

Errors made by participants during the performance of the primary driving tasks and response time for a secondary task were measured for each scenario. Time density of the sensory-motor reaction distribution was described by the formula #1 with five parameters:

$$P(T) = A \cdot (T - T^0)^B \cdot \exp\left(-C \cdot (T - T^0)^D\right). \tag{1}$$

where T^0 is an excess factor,

A - a scale factor

B –a density of distribution increase factor,

C and D – a density of distribution decrease factor.

For each examinee quantities of the mentioned factors were calculated as a result of approximation. After that the following measures were defined: (1) mode of distribution (the most probable size, TM) of reaction time values; (2) half-width of distribution (characterizes disorder of quantities, T) of reaction time quantities. Secondary sensory-motor task performance measure (SST) was calculated by the formula #2:

$$SST = 0.5 \cdot TM + 0.5 \cdot \Delta T. \tag{2}$$

The experiment has begun with the 3-minutes registration of an electrocardiogram for the baseline heart rate variability (HRV) assessment. After that participants have performed three 15-minutes scenarios, then, after a small break - three more scenarios. After the end of the last scenario 3-minute HR registration in the rest period was carried out.

Cardiovascular Measures. Electrocardiogram signals were continuously recorded during the performance of training scenarios by the participants using “Omega-M” portable loggers (Dinamica Inc., Russia) with disposable electrodes. A standard three-electrode configuration was used, as described by Mulder et al. [10]. R-peaks were continuously recorded, with an accuracy of 1 ms. Artifacts were corrected using interpolation. Analyses were made according to the recommendations of the task force on HRV [8]. Time domain measures of HRV included mean RR interval (RRNN), standard deviation of all normal RR intervals (SDNN), and RMSSD (square root of the mean squared difference of successive normal RR intervals). Frequency domain measures of HRV were quantified through the fast Fourier transform and included low frequency power (LF, 0 Hz), high frequency power (HF, 0 Hz), and the LF/HF ratio. Along with it the calculation of following measures was carried out [4]:

Mode (Mo) - most frequently occurring value of R-R.

Amplitude of a mode (AMo) – a ratio of RR-intervals quantity with the values equal to Mo, to the total RR-intervals in percentage.

Range (ΔX) - is calculated as a difference between maximum and minimum values of R-R. It reflects the variability level or peak-to-peak value of RR-intervals.

Index of autonomic balance (IAB)

$$IAB = \frac{AMo}{\Delta X} \quad (3)$$

Index of regulatory systems tension (TI) reflects a level of centralization of heart rate control

$$TI = \frac{AMo}{2 \cdot \Delta X \cdot Mo} \quad (4)$$

The analysis of the heart rate transitive processes under increased workload intensity was carried out by the technique offered by N.I. Sapova [13]. Calculation of peak and time measures of the heart rate transitive processes was carried out.

To assess moment-to-moment changes in HR-variability during the performance of training scenarios **CS-index** calculation was carried out with the formula #3:

$$CS_N(t) = \frac{\langle RRNN \rangle_A \cdot \langle SDNN \rangle_A}{\langle RRNN \rangle_N \cdot \langle SDNN \rangle_N} \quad (5)$$

Where RRNN - stands for average cardio-intervals value for an observation stage;
SDNN – standard cardio-intervals deviation for an observation stage;
<> - averaging on time interval;
t – observation time (position of the window centre);
a - baseline state (3 minutes);
N - averaging procedure for a window which width makes N points. In these calculations CSN (t) the width of a window (N) is equal to 9 points of RR-intervals.

3 Results

3.1 Task Performance Data

At the stage of data analysis we have confirmed that professional experience and a level of task difficulty and critical rail incident appearance affects the successfulness of participant performance of the primary training task and secondary sensory-motor task.

The percentage of errors made by the participants was calculated for each scenario. Measure of a primary training task's (PTT) successfulness performance was calculated on its basis. ANOVA with Task Difficulty (low, medium, high) and Conditions (presence vs. absence of critical incidents) as a within-subject factors and Experience (Novice vs. Experienced train drivers) as a between-subject factor were used. Successful performance of scenarios with critical incidents demanded from participants multitask performance during time pressure and was connected with sharp increase of cognitive workloads. In this connection we considered Conditions factor as one of the task load factors, along with the Task Difficulty factor.

It was discovered that both task load factors affect the successfulness of the primary training task performance. Increase of the training task difficulty leads to deterioration of participant activity and increase in the number of errors (F(2,37) =28,2, p<0,001). In the presence of critical incidents train drivers made more errors than in their absence (F(1,38) =16,00, p<0,001). The significant differences between the groups were determined for driving task performance during stressful scenarios, but not for neutral ones. The novice train drivers have committed more errors in driving in association of critical incidents than experienced train drivers.

Measures of the secondary sensory-motor task performance were analyzed by the same method. Again, both of the task load factors have significantly affected the performance of the sensory-motor task. The response time both for the experienced train drivers and for the novice train drivers has essentially increased in association with critical incidents, indicating the psychological cost of adaptation to stressful conditions (F(1,38)=18,9, p<0.001). Significant differences between the groups were also found (F(1,38) =14,8, p<0,01). The experienced train drivers were more successful in performing the secondary task than the novice train drivers. These results indicate that both task load factors were strong enough to significantly affect task performance. They also indicate that during the performance of training scenarios the majority of participants were sensitive to each of the task load factors.

3.2 Cardiovascular Data

Turning to the heart rate variability indicators, we have evaluated the ability of each indicator to detect changes in cognitive activity of experienced and novice drivers as each of the two task load factors varied. Each physiological measure was analyzed by the same method as the performance measures. It was found that among the measures of heart rate regulation CS measure had the greatest sensitivity to the influence of task load factors. This indicator enables to assess changes of heart rate variability for relatively small time intervals (7-9 seconds). An example of the given indicator's changes at occurrence of the critical incident is presented on the figure #1. Increase in the value of the indicator points at the increased human physiological arousal.

It was found that the Task Difficulty factor significantly affects the CS measure (F(2,37)=44,7, p<0,001). As the conditions of the training task become more complicated, the value of CS-index considerably increases in both groups of

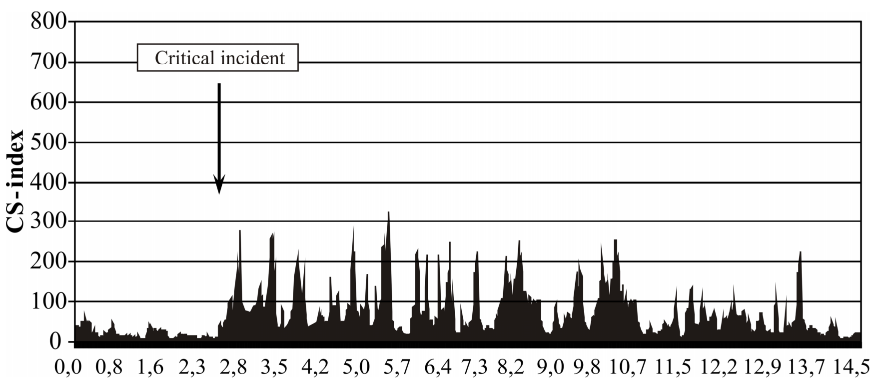

Fig. 1. An example of CS-index dynamics during the performance of stressful training task

participants. During the performance of training tasks associated with critical incidents, experienced and novice train drivers have shown greater values of CS than at the performance of neutral training tasks (F(1,38)=133, p<0,001). Significant interaction of the Task Difficulty and the factor Experience was observed (F(2,37)=7,44, p<0,05). Experienced train drivers in comparison with novice ones had considerably lower level of physiological arousal at the performance of difficult training tasks. It indicates the lower physiological 'cost' of their adaptation to raised cognitive workloads. Results of the analysis are presented at the figure #2.

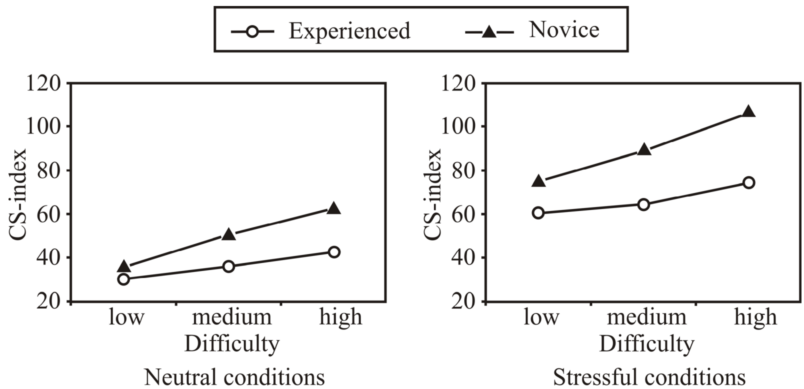

Fig. 2. Influence of Task Difficulty (low, medium, high) and Conditions (neutral, stressful) on CS measure at experienced and novice train drivers

It was established then that a number of HVR-measures offered by R.M. Baevskii [2-5] show relative sensitivity to the influence of load factors. The Condition factor (neutral, stressful) significantly affects the values of the regulatory system tension index (TI) (F(1,38)=25,06, p<0,001) and values of index of autonomic balance (IAB) (F(1,38) =33,4, p<0,001) in both groups of examinees. Measures of the regulatory system tension during the performance of neutral and stressful training tasks are presented on a figure 3. As follows from fig.3, participants had considerably greater values of a TI-index during the performance of stressful training tasks than during the performance of neutral training tasks. The influence of the Task Difficulty factor on the values of TI measures was observed (F (2,37) =5,44, p<0,05). Significant influence of the Difficulty factor on the values of IAB measures is not found (F (2,37) =2,178, p>0,05).

Significant influence of task load factors on frequency domain measures of HRV was not observed during the research.

Further, heart rate transitional characteristics during the occurrence of stressful critical incidents have been analyzed for stressful training tasks. Significant between - group differences in the measures of heart rate transitive processes duration were found (F(1,38) =9,84, p<0,01). Experienced train drivers in comparison with novice ones had considerably shorter duration of the heart rate transient phases during adaptation to high cognitive workloads caused by the occurrence of critical incidents. Influence of the Task Difficulty factor on the measures of transient processes of the heart rate was not significant.

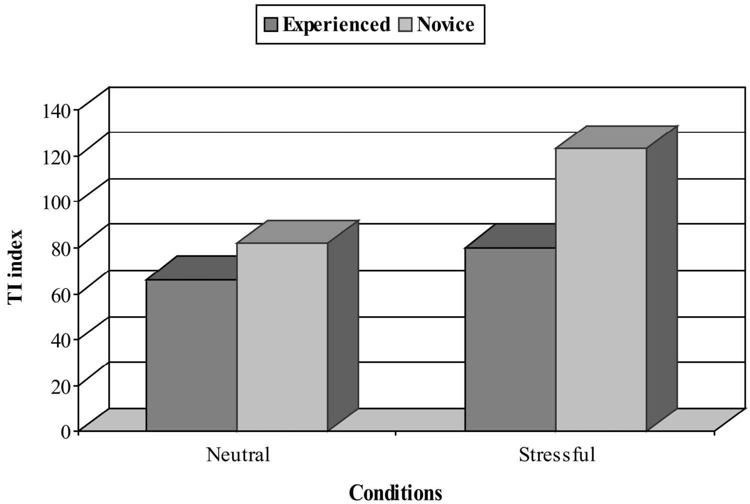

Fig. 3. Average measures of the regulatory systems tension index (TI) during the performance of neutral and stressful training tasks

4 Discussion

Russian researchers have developed a substantial number of physiological methods to assess the efficiency of operator adaptation to high cognitive workloads. Indicators of heart rate regulation (HRR) got the greatest practical application. Methods of variational pulsometry, such as regulatory system tension index (I), a measure of regulation processes adequacy (MRPA), index of autonomic balance (IAB) and other methods are widely applied in operator cognitive workloads assessment during the real or simulated professional work [2, 4]. These indexes are based on the analysis of characteristics of R-R intervals distribution. They are assessed for 3-minute time intervals and do not enable to identify moment-to-moment changes in operator cognitive activity.

In this context a new method of HRV analysis called CS-index is offered [7]. It enables to reveal moment-to-moment changes of operator's physiological arousal level during the performance of professional tasks. The approach based on the analysis of heart rate unsteady characteristics was offered along with it, enabling to assess the success of student's adaptation to specific kinds of workloads.

The purpose of the present research was to empirically assess the ability of various heart rate measures to identify changes in cognitive activity of novice and experienced drivers during the professional task performance.

It was found that during the performance of training scenarios associated with stressful incidents participants had considerably greater values of the regulatory system tension index (TI) than during the performance of scenarios not connected with stress. It confirms the data of other studies indicating that the TI index is a reliable sign of the emotional stress level experienced by operator during the work performed [5].

It was discovered, that the indicator to assess a heart rate variability called the CS-index is more sensitive to the influence of both workload factors. Increase of the training task complexity and occurrence of critical incidents led to considerable increase of the CS-index average values in both groups of participants.

The present research has also confirmed the dynamic measure informativity, such as duration of the heart rate unsteady processes during changing workloads. It was shown that experienced driver measures of unsteady processes duration were significantly less than in the novice group. It points to their more successful adaptation to the influence of the raised workloads.

It is obvious that the further research directed to validity and reliability demonstration of the considered methods of heart rate regulation assessment is necessary. If their validity and reliability are proven, it may be perspective to integrate the given methods with the Automated Expert Modeling for Automated Student Evaluation (AEMASE) approach developed by Sandia National Laboratories [1]. This will permit to raise the efficiency of expert training.

References

1. Abbott, R.G.: Automated expert modeling for automated student evaluation. Intelligent Tutoring Systems, 1–10 (2006)
2. Baevskii, R.M.: Analysis of Heart Rate Variability in Space Medicine. Human Physiology 28(2), 202–213 (2002) (in Russian); Баевский Р.М. Анализ вариабельности сердечного ритма в космической медицине. Физиология человека, 2, с. 34–43 (2001)
3. Baevskii, R.M.: Prediction of states on the verge of norm and pathology. Medicine Publ., Moscow (1979) (in Russian); Баевский Р.М. Прогнозирование состояний на грани нормы и патологии. Москва: Медицина (1979)
4. Baevskii, R.M., Ivanov, G.G.: Heart rate variability: theoretical aspects and possibilities of clinical application. Medicine Publ., Moscow (2000) (in Russian); Баевский Р.М., Иванов Г.Г. Вариабельность сердечного ритма: теоретические аспекты и возможности клинического применения. Москва: Медицина (2000)
5. Baevskii, R.M., Kirillov, O.I., Kletskin, S.Z.: The mathematical analysis of changes of a cardiac rhythm at stress. Nauka Publ., Moscow (1984) (in Russian); Баевский Р.М., Кириллов О.И., Клецкин С.З. Математический анализ изменений сердечного ритма при стрессе. М., Наука (1984)
6. Bogomolov, A.V., Gridin, L.A., Kukushkin, Y.A., Ushakov, I.B.: The diagnostics of human state: Mathematical Approaches. Medicine Publ., Moscow (2003) (in Russian) Богомолов А.В., Гридин Л.А., Кукушкин Ю.А., Ушаков И.Б. Диагностика состояния человека: математические подходы. - М.: Медицина (2003)
7. Bozhokin, S.V., Petrukovich, V.M., Negrusha, N.A., Inozemtzev, S.A.: Vegetative modulation of heart rate under psychophysiological loads. Vestnik Rossiiskoi voenno-meditsinskoi akademii (News of Russian Military-Medical Academy) 1(17), 332 (2007) (in Russian); Божокин, С.В., Петрукович, В.М., Негруша, Н.А., Иноземцев, С.А. Вегетативная модуляция сердечного ритма при психофизиологической нагрузке // Вестник Российской Военно-медицинской академии, приложение 1(17), С. 332 (2007)
8. Camm, A.J., Malik, M., Bigger, J.T., Breithardt, G., Cerutti, S., Cohen, R.J., Coumel, P., Fallen, E.L., Kennedy, H.L., Kleiger, R.E., Lombardi, F., Malliani, A., Moss, A.J., Rottman, J.N., Schmidt, G., Schwartz, P.J., Singer, D.H.: Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Eur. Heart J. 17, 354–381 (1996)

9. Medvedev, V.I.: Human's physiological and psychological functions' resistance under the influence of extreme factors. Science Publ., Leningrad (1982) (in Russian); Медведев, В.И.: Устойчивость физиологических и психологических функций человека при действии экстремальных факторов. Ленинград, Наука (1982)
10. Mulder, L.J.M., de Waard, D., Brookhuis, K.A.: Estimating mental effort using heart rate and heart rate variability. In: Stanton, N., Hedge, A., Brookhuis, K.A., Salas, E., Hendrick, H. (eds.) Handbook of Human Factors and Ergonomics Methods. CRC Press, Boca Raton (2004)
11. Novikov, V.S., Shustov, E.B., Goranchuk, V.V.: Correction of functional states under extreme exposures. Science Publ., St. Petersburg (1998) (in Russian); Новиков, В.С., Шустов, Е.Б., Горанчук, В.В. Коррекция функциональных состояний при экстремальных воздействиях. - СПб.: Наука (1998)
12. Parin, V.V., Baevskii, R.M.: Methods of heart rate's mathematical analysis. Science Publ., Moscow (1968) (in Russian); Парин, В.В., Баевский, Р.М. Математические методы анализа сердечного ритма. Москва: Наука (1968)
13. Sapova, N.I.: Complex evaluation of heart rhythm regulation during measured functional loads. Fiziologicheskiĭ zhurnal SSSR imeni I. M. Sechenova (Sechenov physiological journal of the USSR) 68(8), 1159–1164 (1982) (in Russian); Сапова, Н.И. Комплексная оценка регуляции сердечного ритма при дозированных функциональных нагрузках // Физиол. журн. им. Сеченова 68(8), С. 1159–1164 (1982)
14. Zhernavkov, V.F., Kozlovsky, E.A.: Psychophysiological assessment of pilots' readiness on the flight simulators. Voenizdat (Military Publ. House), Moscow (1981) (in Russian); Жернавков, В.Ф., Козловский, Э.А. Психофизиологическая оценка подготовленности летчика на пилотажных тренажерах. Москва: Воениздат (1981)
15. Zotov, M.V., Petrukovich, V.M., Zhuravleva, O.P., Inozemtzev, S.A., Voit, A.P.: The automated systems of dynamic control of the operators' emotional state and professional working capacity. Vestnik Rossiiskoi voenno-meditsinskoi akademii (News of Russian Military-Medical Academy). 1 (15), pp. 442-443 (2006) (in Russian) Зотов, М.В., Петрукович, В.М., Журавлева, О.П., Иноземцев, С.А., Войт, А.П. Автоматизированная система динамического контроля функционального состояния и профессиональной работоспособности операторов. Вестник Российской Военно-медицинской академии, приложение, 1(15), С. 442–443 (2006)