Functional Determination of the Operator State in the Interaction of Humans with Automated Systems

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SUMMARY

To predict future problems and prevent difficulties with human-automation interaction and coordination, we need to evaluate dynamically the three components of the complex human-socio-technical system: human operators, social characteristics, and automation/technology. Under conditions of work in an automated system operators are exposed to the effects of mental load and work stress factors. These factors are a function of the automated system. Highly automated agents introduced in the system to contribute to human problem solving impose new cognitive and information processing demands, and might increase the level of workload and stress. The potential of human operators to interact adequately with and to coordinate the automated systems in normal and in critical conditions depends on the assessment and prediction of the operator's mental state. The goal of our study is to determine the effect of workload and work stress components on operator functional state as a function of an automated system, and to examine functional relationship between both factors. The results of our study indicate that contrary to mean values of actual and intrinsic heart rate, the Heart Rate Variability (HRV) spectral components: P_T , P_{THM} , P_{RSA} are significant indicators for the assessment of operator state. Human-automated system interaction exerted greater strain in telecommunication operators, ATC, and computer operators as revealed by the P_T , P_{THM} , P_{RSA} and mean R-R interval changes. Both sympathetic and parasympathetic activity modulating frequency-domain HRV measures decreased as a function of mental workload. An attempt was made to define a model discriminating human-system/human-computer interaction. Controllability of work situation, quantitative workload, variance in workload, and work satisfaction discriminate human-system- from human-computer interaction. In our

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study we observed a functional relationship between cognitive workload, assessed by HRV and HR, and work stress measured by work-related psychosocial factors. Functional dependence of cognitive demands and work satisfaction on vagal activity assessed by P_{RSA} *could promote future research on the association between cognitive workload, work stress, and performance in considering the role of* P_{RSA} *as an indirect measure of performance and as a direct indicator of the cardiovascular protective function. The results of our field studies clearly indicate that operators are exposed to the effects of cognitive load and work stress factors which are function of their interaction with an automated system.*

INTRODUCTION

Progress in science, information technology, automation, and all spheres of the intellectual, work, and social development of society in the 21st century has been inspired by the unlimited possibilities of human spirit, intellect, and creativity. The work environment embodies these processes of transformation in contemporary society. The human operator and automated and intelligent systems are the critical elements of this transformation.

To predict future problems and prevent difficulties with human-automation interaction and coordination, we need to evaluate dynamically the three components of the complex human-socio-technical system: human operators, social characteristics, and automation/technology [23; 25; 28]. To understand successes and failures in complex human-automated systems we have to determine and evaluate the effects of mental load and stress in complex task environments, examine psychosocial factors of the work environment; and design and control automated and intelligent systems that assist and enhance the work of humans and ensure the safety of human life [2-5; 7-9; 12-14; 16-18; 21-23; 33; 35; 38; 41; 42; 45; 46; 48].

This century imposes requirements for adequate functioning, interaction, and coordination of humans with intelligent systems. Either side of this interaction could contribute to a system of defense against terrorism, elimination of crucial micro- and macroergonomic errors in performance of strategic or occupational tasks. Examples from the past of system breakdown are non-compliance with critical factors: failures in system components and their interaction; failures in system environmental factors [21] such as in the accidents at Chernobyl, Bhopal, and Three Mile Island.

Work in conditions and within the framework of automated, human-socio-technical systems is characterized by risk of unanticipated variability of their components and parameters [37]. Successive managing of the automated system is dependent on the capability of the human operator to take actions and to make decisions in normal and in critical situations. As a consequence the operator’s role has changed from rule follower to problem solver [16; 27; 38] and skills shift from psychomotor to cognitive functioning and problem solving [26; 28; 49]. Highly automated agents introduced in the system to contribute to human problem solving impose new cognitive and information processing demands. Monitoring and managing of the system over prolonged periods of time induces a high level of mental workload [36; 38]. Workload has increased because of the cognitive effects associated with monitoring and managing the automation [29; 38].

Variations in workload have required determining the cognitive capacity of the operator’s functioning [37; 40; 43]. An essential component for the regular interaction of humans with automated systems is the evaluation and prediction of the operator’s optimal functional state in the work environment [1; 15; 29]. Suboptimal functional states could induce deterioration in performance and risk of health complications [1; 40]. Indices of cardiac activity, heart rate and heart rate variability (HRV), are sensitive and reliable psychophysiological measures for assessing mental workload and stress [5; 10; 12; 13; 18; 20; 24; 25; 31; 37; 40; 44].

These measures reflect changes in the level of the operator's mental effort and mental load. Spectral HRV measures reveal the extent of mental effort required of the operator to sustain the required level of cognitive performance [20]. This psychophysiological research has underlined the sensitivity of P_{RSA} as an index of parasympathetic activity in testing human factors and evaluating complex automated military and civilian systems. HR and HRV measures can assess major effects of work computational and compensatory effort [2; 40]. Performance of effortful mental tasks was related to a significant reduction in HRV in laboratory and field conditions, and it was hypothesized to be a result of the defence reaction which was associated with a decrease in baroreflex sensitivity [40].

In work activity associated with interaction with highly automated agents imposing a cognitive load, operators are exposed to the influence of psychosocial factors of the work environment. Work with automated systems requires a greater demand on cognitive resources: working memory, attentional processes, decision making, and planning [41]. The high cognitive demands of work activity can lead to a stress reaction if they are associated with a low level of control over the work environment [10; 23; 42]. A low level of control of the work environment was observed to be related to a decrease of parasympathetic activity assessed by P_{RSA} in a study examining the effect of work-related factors: effort, reward, effort-reward imbalance, need to control, type of work, and negative affectivity [10].

Requirements to work in interaction with automated and intelligent systems expose human operators to the increased effect of mental load and work stress. The goal of work with automated systems is to achieve an optimal functional state, to optimize and regulate the level of workload, and to improve performance [4]. Prolonged work in conditions of increased workload and work stress as well as work in critical conditions can induce a dysfunctional pattern of regulation. HRV is a reliable index of disturbed regulatory activity. A disturbed mode of regulatory control has been associated with a suboptimal functional state that can lead to performance breakdown and system failures.

The aim of our study is to determine the effect of workload and work stress components on operator functional state as a function of the automated system, and to examine functional relationships between both factors.

METHODS

1.0 Subjects

Four groups of operators and one referent group participated in the study: operators from telecommunications, military pilots, computer operators, air traffic controllers (ATC), referents. Work activity of operators in telegraph communications, military pilots, and Air Traffic Control (ATC) is associated with a process of interaction and coordination with the automated systems. Work activity of computer operators is representative of the characteristics of human-computer interaction. Characteristics and descriptive statistics of each group are provided in Table 1.

The first group (G1) consisted of 99 operators from telecommunications working with information technology systems. The second group (G2) consisted of 96 military pilots working with military defence systems from the Bulgarian Military Air Force. The third group (G3) consisted of 61 operators working with computers from petroleum construction and assembly industry. The fourth group (G4) consisted of 57 air traffic controllers (ATC) working with automated systems for control of civil air traffic from the Bulgarian Civil Aviation "Balkan". The fifth group (G5) is a referent group and consisted of 42 institute clerks who are not required to work with automated systems.

Table 1: Group Statistics

Group	Occupation	N	Age (years +/- SD)*	Gender (% female)	Tenure (years +/- SD)*	Human-System/Computer Interaction
G1	Telecommunication operators	99	43.06 (8.46)	0	21.2 (9.37)	Human-Automated System
G2	Military Pilots	96	41.41 (7.28)	0	18.5 (8.9)	Human-Automated System
G3	Computer operators	61	39.54 (10.15)	0	17.34 (9.57)	Human-Computer
G4	ATC	57	32.2,8 (6.47)	0	19.8 (8.6)	Human-Automated System
Referent	Institute clerks	42	34.13 (11.800)	0	17.4 (9.6)	–

*One way ANOVA ($p < .01$)

Criteria for exclusion included: systolic blood pressure >130 mmHg; diastolic blood pressure >85 mmHg; body-mass index (kg/m^2) >25; use of medications; smoking; cholesterolaemia; diabetes; and a history of cardiovascular, respiratory, renal, gastrointestinal, hepatic, or systemic disease.

2.0 Procedure

HRV measures data were determined from 10-min ECG recordings between 9 a.m. and 11 a.m. in a supine position after a one-hour rest period. HRV data were obtained on three consecutive days and mean individual values were calculated.

Heart Rate Variability

A computerized method was used to analyze HRV [47]. The ECG was registered from a bipolar standard lead I. A portable electronic device was used to transform the ECG signal into R-R intervals and to transfer the data to an IBM compatible PC for on line processing. The ECG signal is transformed to R-R intervals by an AC convertor (QRS detector and timer, resolution time 2224 samples per second). This sampling rate gives a variation of 0.48 msec in locating the peak of the R wave and results in a minimum accuracy of 99.55 % in computing heart rate up to 140 beats/min.

Time- and frequency-domain measures were analyzed:

1) Time-domain HRV measures: mean R-R interval (msec)
2) Frequency-domain HRV measures:
   - Spectral power of the R-R intervals in the Temperature band (0.00-0.04 Hz) (P_T) (ms^2) (sympathetically mediated);
   - Spectral power of the R-R intervals in the Traube-Hering-Mayer band (0.05-0.14 Hz) (P_{THM}) (ms^2) (sympathetically and parasympathetically mediated);
   - Spectral power of the R-R in the Respiratory Sinus Arrhythmia band (0.15-0.5 Hz) (P_{RSA}) (ms^2) (parasympathetically mediated).

Actual Heart Rate (HR)

Mean value of heart rate was calculated in beats/min from the computer program of HRV analysis.

Intrinsic Heart Rate (HRo)

Intrinsic heart rate was calculated according to the Rosenblueth-Simeone model [39]. HR = m * n * HRo where HR is actual heart rate, m is a factor representing sympathetic acceleration, n is a factor representing vagal deceleration, and HRo is the intrinsic heart rate. The factors m and n may be thought as sympatho-vagal balance [38]. In supine rest values of m and n are, respectively, 1.15 and 0.6. In this study we tested the hypothesis that the mean values of HRo could be utilized for the purposes of psychophysiological research, and to determine whether this parameter could be used for assessment of mental workload and job stress in human-system/computer interaction.

Work Related Psycho-Social Factors

Work related psychosocial factors were evaluated with the NIOSH test for subjective assessment of occupational stress, adapted to Bulgarian conditions and language [30]. The following constructs were examined: 1. Work stressors: variance in workload, quantitative workload, utilization of skills, cognitive demands, controllability; 2. Psychological reactions: work satisfaction; 3. Personal individual factors: self esteem; 4. Buffer factors: social support.

Data Analysis

HR, HRo, HRV are expressed as mean ± standard deviations. Means of HR, HRo, HRV were compared by one-way way ANOVA. Spearman’s rho was used to evaluate the correlations between HR and HRV in the respective groups. Linear regression analysis was applied to determine: dependencies of HRV measures on HR in the studied groups; dependencies of work-related factors on HR and HRV measures in the whole set. Logistic regression analysis (method forward: LR) [6] was used to define measures that discriminate groups working in conditions of human-system and human-computer interaction interaction. A p-value less than 0.05 was considered statistically significant.

RESULTS

1.0 Workload Differences

To examine the extent to which the functional state of operators differed in the five study groups, the cardiovascular measures were compared between groups by one-way ANOVA. The actual heart rate, intrinsic heart rate and HRV measures in each group are expressed as means (standard deviations) in Table 2.

Table 2: Dependent Variables (X+/-SD)

	Group 1	Group 2	Group 3	Group 4	Referent
Variables	X+/-SD	X+/-SD	X+/-SD	X+/-SD	X+/-SD
Mean R-R (msec)	743.85 (218.17)	784.46 (113.96)	755.21 (179.38)	821.79 (121.39)	857.31 (118.73)
Actual Heart rate (beats/min)	71.64 (22.36)	77.56 (11.31)	75.89 (18.32)	74.56 (10.52)	70.42 (9.81)
Intrinsic Heart Rate (beats/min)	103.82 (32.41)	112.41 (16.4)	109.98 (26.56)	108.06 (15.25)	100.72 (14.32)
P_T (ms^2)	4.90 (2.57)	6.02 (2.68)	5.25 (2.40)	4.41 (2.45)	7.01 (2.45)
P_{THM} (ms^2)	5.33 (3.28)	8.37 (3.57)	5.86 (2.78)	4.35 (2.55)	8.38 (2.85)
P_{RSA} (ms^2)	5.07 (3.09)	6.12 (3.37)	6.13 (3.34)	4.38 (2.50)	8.65 (3.56)

Inter-group comparison revealed that workload significantly affected mean R-R interval, P_T, P_{THM} and P_{RSA}. In contrast, the actual and intrinsic heart rate did not discriminate significantly between the examined groups.

Workload was related to a significant decrease in mean values of P_T in telecommunication operators compared to military pilots and referents. Workload induced a significant decline of mean values of P_{THM} in telecommunication operators compared to military pilots and referents, and in ATC compared to military pilots, computer operators and referents.

Workload was associated with a significant decrease of mean values of P_{RSA} in telecommunication operators compared to military pilots, computer operators, referents; in ATC compared to military pilots, and in computer operators compared to referents. Mean values of mean R-R interval decreased significantly in telecommunication operators, military pilots compared to ATC and referents.

2.0 Effect of Workload on Autonomic Cardiovascular Control

2.1 Correlations of HR with HRV

- In telecommunication operators were observed: Significant negative correlation of HR with frequency-domain HRV measures: P_T (r=-0.358, p<0.0001); P_{THM} (r=-0.282, p=0.007); P_{RSA} (r=-0.425, p<0.0001).
- In military pilots were observed: Significant negative correlation of HR with frequency-domain HRV measures: P_T (r=-0.388, p<0.0001) and P_{RSA} (r=-0.425, p<0.0001).
- In computer operators were observed: Significant negative correlation of HR with P_{RSA} (r=-0.315, p=0.02).
- In ATC were observed: Significant negative correlation of HR with frequency-domain HRV measures: P_{THM} (r=-0.397, p=0.002); P_{RSA} (r=-0.463, p<0.0001).
- In referents: Significant correlations were not observed.

2.2 HRV Dependencies on HR

In the entire data set it was observed that HR declined as a function of $P_{RSA.}$ The same pattern was observed in differentiated groups: telecommunication operators, computer operators and ATC. In contrast, the military pilot group revealed P_T dependence on HR. In the referent group significant regression dependence of HRV on HR was not observed. Regression coefficients are presented in Table 3.

Table 3: Significant Regression Coefficients of Dependence of HRV on HR.

Variables		Entire set	Telecom. operators group	Military Pilot group	Computer operators group	ATC group	Referent group
Frequency-domain HRV measures							
	P_T	–	–	-2.23***	–	–	–
	P_{THM}	–	–	–	–	–	–
	P_{RSA}	-1.42***	-2.25***	–	-1.58***	-1.79***	–

***p<0.0005

3.0 Functional Dependencies of Work Related Factors on Cognitive Workload Assessed by HRV and HR.

HR and HRV measures have changed as a function of work related factors in the entire set. Regression equations describing dependencies of work related factors on HRV and HR are presented in table 4.

- Time-domain HRV measures: Mean R-R interval decreased progressively as a function of utilization of skills and cognitive demands.
- Frequency-domain HRV measures: Differentiated spectral powers of R-R intervals in the P_{THM} and P_{RSA} bands changed slowly with an increase in effect of work environmental factors, compared with time-domain measures. P_{THM} increased as a function of work satisfaction whereas P_{RSA} showed an opposite trend: increasing as a function of work satisfaction and decreasing as a function of cognitive demands.
- HR increased as a function of utilization of skills.

Table 4: Regression Equations of Dependence of Work Related Factors on HRV and HR

$$\mathbf{P_{THM}} = 3.179 + 1.278 * \text{ x Work Satisfaction}$$

$$\mathbf{P_{RSA}} = 1.975 - 1.238 * \text{ x Cognitive Demands} + 1.115 * \text{ x Work Satisfaction}$$

$$\textbf{Mean R-R} = 671.077 - 97.767 * \text{ x Utilization of Skills} - 86.652 * \text{ x Cognitive Demands}$$

$$\textbf{HR} = 105.188 - 4.029 * \text{ x Utilization of Skills}$$

*p<0.05

4.0 Discrimination of Human-System from Human-Computer Interaction Groups

Logistic regression analysis (method forward: LR) (3) contributed to the discrimination of telecommunication operators required to work in conditions of interaction with highly automated systems in operators whose working activity is characterized by human-computer interaction. Four variables: controllability of work situation (C), quantitative workload (QW), variance in workload (VW) and work satisfaction (WS) discriminate human-system- from human-computer interaction groups in this study (fig. 1). Probability one investigated subject to refer to human-system interaction group is assessed by first equation in fig. 1. The probability of an investigated individual to be a computer interactive element is assessed by a second equation in fig. 1. The general discrimination power was 94.6 %. With the exception of one telecommunication and computer operator all individuals were correctly classified.

$$P_{(CC=0)} = \frac{1}{1 + e^{-(24.37 - 3.95\times C + 2.3\times QW + 2.58\times VW - 2.69\times WS)}}$$

$$P(CC = 1) = 1 - P(CC = 0)$$

0 - human-system interaction group; 1 – human-computer interaction group

Figure 1: Equations of the Logistic Regression Analysis (Method Forward: LR).

DISCUSSION

The potential of human operators to interact adequately with and to coordinate an automated systems in normal and in critical conditions depends on the assessment and prediction of the operator's mental state. HRV measures are reliable and sensitive indices for the examination of mental effort invested in the monitoring and managing system. The results of our study indicate that contrary to mean values of actual and intrinsic heart rate, the HRV spectral components: P_T , P_{THM} , P_{RSA} are significant indicators for the assessment of operator state. Human-automated system interaction exerted greater strain in telecommunication operators, ATC and computer operators as revealed by the P_T , P_{THM} , P_{RSA} and mean R-R interval changes. Both sympathetic and parasympathetic activity modulating frequency-domain HRV measures decreased as a function of mental workload. These results are consistent with the findings of Mulder et al., 2000 [11] and Miller and Rokicki, 1996 [20] who reported a decrease in HRV spectral components under increased mental load. The sensitivity of HRV is observed also in the experimental research of Karemaker, 1987 [19] who emphasized on the significance of the variability and regularity of beat-by-beat cardiac activity associated with prevailing vagal function.

Under conditions of work in an automated system heart rate change is dependent on parasympathetically mediated P_{RSA}. This result was observed in all subjects and in differentiated groups: telecommunication operators, ATC and computer operators. Military pilots revealed sympathetically mediated (P_T) dependence on HR. In the referent group we did not observe dependence of HRV on HR suggesting that autonomic control was not affected.

The most likely reason for observed decline in parasympathetic activity assessed by P_{RSA} is the sustained effect of workload demands under prolonged exposure to work activity in conditions of human-system/human-computer interaction. The decreased protective role of vagal activity could be associated with health risk and suboptimal functional state that might provoke future performance deterioration. Mechanisms that could induce a suboptimal functional pattern are decreased parasympathetic activity mediating P_{THM} and P_{RSA} and decreased baroreceptor modulation of heart rate assessed by P_{THM}.

An attempt was made to define a model discriminating human-system/human-computer interaction. Controllability of work situation, quantitative workload, variance in workload and work satisfaction discriminate human-system from human-computer interaction. This result might indicate that telecommunication operators were exposed to increased cognitive demands in their work activity.

Psychophysiological and occupational research has considered the dependence of stress and lowered work satisfaction on work demands as basic [8; 9; 12; 23; 41; 42]. In our study we observed a functional relationship between cognitive workload assessed by HRV and HR, and work stress measured with work-related psychosocial factors. Our result is consistent with the result of Hockey et al., [41] who reported a functional association between workload and work stress. Our country is in transition period, and work activity is associated with difficulties in adaptation to new technologies, the necessity of acquiring new skills and knowledge, working with new technologies, etc. The prolonged effect of work related factors could induce an abnormal pattern of regulatory activity and could affect cardiovascular regulatory mechanisms: parasympathetic function – P_{RSA} , and baroreceptor modulation of heart rate – P_{THM} (table 6). The functional dependence of cognitive demands and work satisfaction on vagal activity assessed by P_{RSA} could promote future research on the association between cognitive workload, work stress, and performance in considering the role of P_{RSA} as an indirect measure of performance [18] and as a direct indicator of the cardiovascular protective function. The results of our field studies clearly indicate that operators are exposed to the effects of cognitive load and work stress factors which are function of their interaction with an automated system.

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