EFFECT OF WORKLOAD AND STRESS ON OPERATOR FUNCTIONAL STATE

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ABSTRACT

Abstract. Complex work environments require human operator to process considerable information and to sustain an adequate level of control. Both mental workload and stress associated with environmental and psychological factors affect cognitive functioning as reflected in functional state and work performance. One of the goals of human state regulation is determination of functional and dysfunctional modes of activation that could serve as indicators of increased risk of performance breakdown. The aim of this study is to analyze the effect of workload and stress on operator functional state in military pilots, drivers, Mill factory operators and bank operators, and to predict future performance decrement. Functional state of the cardiovascular system was determined by examining actual heart rate, intrinsic heart rate and Heart Rate Variability (HRV) measures. In Bulgaria in our work environment of the post-totalitarian society we cannot separate the effect of mental workload, environmental, social and economic stress factors on operator functional state as the individuals are exposed to the complex interactions of their work. Intrinsic and actual heart rate as well as spectral components of HRV change as a function of this complex interaction. Most sensitive to workload and stress are intrinsic and actual heart rate, and spectral powers of R-R intervals, resp. in the Respiratory Sinus Arrhythmia band (0.15-0.5 Hz) (P_{RSA}) and in the Traube-Hering-Mayer band (0.05-0.14 Hz) (P_{THM}) in Mill factory operators and military pilots.

Constant suboptimal functional response pattern after prolonged exposure to mental workload and stress was observed in Mill factory operators, military pilots and drivers. Mechanisms that may induce suboptimal response pattern are chronic sympathetic stimulation which increases slow diastolic depolarization, decreased parasympathetic activity mediating P_{RSA} and P_{THM} , and decreased baroreceptor modulation of heart rate, assessed by P_{THM} . By examining RSA we infer that the occupational groups most likely affected by eventual performance decrement are Mill factory operators, military pilots and drivers. However in our study the operators did not reveal complete suppression of RSA, and exact determination of performance status can be accomplished with an investigation of performance.

1. INTRODUCTION

Complex work tasks require a human operator to process considerable information and to sustain an adequate level of control and effort. The process of interaction and management of complex systems and tasks imposes increased mental demands. The final goal in human information processing is to achieve effective task performance.

The experience of workload is determined by the task load and the interaction of the following factors: task demands, expended effort, and level of performance [17]. Cognitive abilities of operators to discriminate information intake; to regulate the level of control, effort and alertness; and to function and respond adequately are features of routine situations. Such tasks are associated with specific patterns of energetical state associated with information processing and adaptive response to environmental task demands [11, 34]. The approach of cognitive energetics is particularly useful in being able to recognize regulatory activity of sub-systems and end-organs operating in conditions of stress and environmental load [17; 34; 18].

Byrne and Parasuraman (1996) [5] defined cognitive effort as an involuntary process produced by external tasks demands, and compensatory effort as an energetic process under voluntary control of the individual. A debatable issue is whether there is a distinction between these two types of efforts or whether they are an statement of one general mechanism [3; 4]. Contrary to regular working activity, working activity in suboptimal conditions is characterized by increased compensatory effort investment [44; 34].

In assessing psycho-physiological costs depending on period of exposure it was demonstrated that such states can be maintained without disturbance for short time periods. Prolonged highly demanding work is stressful and characterized by disruption of the normal homeostatic regulatory processes, increased cognitive strain, and fatigue [9; 11].

In considering the definition of mental workload as a ratio between task demands and capacity, we have to recognize factors determining the capacity, including the influence not only of skills, education, and training but also such stressors as sleep deprivation, fatigue, noise, etc. [9; 44]. In complex task environments human operators adapt to increased demands of working activity by exerting additional mental effort to maintain a constant level of performance [44].

However, there is pronounced difference between the complex task environment of well-developed Western societies and the post-totalitarian societies. The difference is due to the high level of psycho-social stress in the latter. The increased stress level operates on cognitive mental processes. Operators from the Western societies also experience such stress [19], but in most cases it affects the respective social group but not the whole society, and the stressors are different. In these societies social and economic processes are developed and are settled in an evolutionary and gradual way, and these processes had not caused such conflict and cataclysms as in our society. In post-totalitarian society we see a revolution in thinking, working, and living as the totalitarian way of life was completely rejected. Work now occurred in conditions of economic collapse with difficulties in adaptation to new conditions; the necessity of acquiring new skills and knowledge; working with new technologies; ignoring the role of the state in employment and social status; reducing the employment staff; etc. The health situation of individuals from Central and Eastern Europe and its relation to social, economic, and risk factors of CVD has been extensively discussed [35; 43]. Both mental workload and stress associated with environmental and psychological factors affect cognitive functioning, as reflected in functional state and work performance [2]. The functional response of the operators is determined by the balance between demands placed on the individual and the available resources and the ability to cope with the task demands.

Utilization of resources requires the operation of physiological mechanisms that can be detected with psycho-physiological measures [1; 4; 17; 18; 23; 26; 27; 28; 29; 36; 37; 44; 45]. The most frequently analyzed and assessed cardiovascular measures of mental workload in complex task environments are heart rate and heart rate variability (HRV) [4; 5; 7; 11; 14; 15; 16; 17; 18; 25-29; 31; 33; 34; 36; 37; 38; 41; 42; 44; 45; 46]. These cardiovascular measures are reliable parameters for the assessment of mental workload [7; 37; 46].

However research views differ with regard to their significance for cognitive load. Wilson (1992; 1993) considers heart rate as a better measure of operator workload in real flight operations in pilots and weapon systems officers than HRV. The same view is supported by Grossman and Svebak, (1987) [11]; Kamphuis and Frowein (1985) [18]. Heart rate has been used as a physiological correlate of the subjective underload state and mental effort [18; 19; 24]. Heart rate response is believed to be related to task-associated anxiety (17; 38). In addition under mental workload an increase in heart rate and a decrease of HRV have been observed [26].

Another research view regards frequency-domain measures of HRV and particularly the spectral power of the interbeat intervals (R-R) centered around the 0.1 Hz component as sensitive measures of workload demands in laboratory and filed conditions [1; 41; 25; 27; 28]. An increase in invested mental effort was reflected in reduced spectral power of R-R in the Traube-Hering-Mayer wave (P_{THM}), causing reduced sensitivity of the baroreflex regulating mechanism with diminished control on the sinus node [1; 27; 28; 42]. Sensitivity of the P_{THM} component is reported as a specific measure for the assessment of the knowledge-based problem solving task [37], and a decrease of the amplitude of this component indicates increased effort expenditure [17]. Also sensitive to invested effort in a mental task is the spectral power of R-R in the low-frequency Temperature band (P_T) [18]. This spectral measure is even more sensitive than the P_{THM}. Mental workload can provoke changes in the spectral power of R-R in the Respiratory Sinus Arrhythmia band (P_{RSA}) [36].

Another convincing thesis supports the view that the three spectral HRV components are affected under conditions of increased mental activity (decreased spectral power), indicating that the three indices may be used for the assessment of mental workload. Studies of Kampius and Frowein (1985) [18]; Mulder (1988) [26] revealed that the P_{RSA}, P_T and total HRV are more sensitive to behavioral dimensions than the P_{THM}.

Reported results observed under conditions of mental workload tasks in laboratory and field conditions clearly demonstrated that heart rate and spectral measures of HRV could be equally utilized for the assessment of cognitive processes. They are reliable and non-invasive measures of autonomic cardiovascular control and are extensively applied in the examination of mental workload. One of the goals of human state regulation is determination of functional and dysfunctional modes of activation and energy mobilization that could serve as indicators of increased risk of performance breakdown. Short-term stress states may promote the operator to mobilize his own resources, to increase his effectiveness, and to perform the task. Prolonged stress states could be associated with a dysfunctional mode of regulatory activity characterized by allostatic patterns of prolonged or inadequate response to the stressor.

Prolonged stress could induce deterioration of performance with increased risk of breakdown. Human freedom, safety, and health in a complex task environment require early detection and identification of failures in task characteristics, complex systems, and environmental stress states.
The aim of our research is to analyze the cognitive effects of workload and stress on operator functional state, and to predict future performance decrement. Functional state of the cardiovascular system was determined by examining actual heart rate, intrinsic heart rate and HRV measures.

METHODS

2. 1. Subjects

Five groups of operators and one referent group participated in the study: two groups of military pilots, drivers, Mill factory operators, bank operators, librarians. Characteristics and descriptive statistics on each group are provided in Table 1.
The first group (G1) consisted of 66 military pilots employed by the Bulgarian Military Air Force, and students of the Bulgarian Military Air Academy. The second group (G2) consisted of 96 military pilots employed by the Bulgarian Military Air Force, and students of the Bulgarian Military Air Academy. For the purpose of the study first two groups were not combined due to the significant differences in the mean value of job tenure in the occupation. The third group (G3) consisted of 30 drivers, their working activity is associated with exposure to noise and vibration. The fourth group (G4) consisted of 68 operators of Mill factor, in their working activity operators were exposed to noise and dust. The fifth group (G5) consisted of 47 bank operators whose working activity was associated with mental load. The sixth group is referent group and consisted of 39 librarians who are not exposed to stress load in their working activity.

Table 1. Group Statistics

Group	Occupation	N	Age (years +/- SD)*	Gender (% female)	Tenure (years +/- SD)*	Occupational Exposure
G1	Military Pilots	66	34.85 (10.7)	0	12.2 (10.3)	Mental and Environmental Load
G2	Military Pilots	96	41.5 (7.3)	0	18.5 (7.3)	Mental and Environmental Load
G3	Drivers	30	46.1 (11.8)	60	22.28 (9.7)	Noise and Vibration
G4	Mill Workers	68	45.2 (9.2)	42	25.5 (9.3)	Noise and Dust
G5	Bank Operators	47	53.2 (12.6)	61	25.3 (9.3)	Mental Load
Referent	Librarians	39	33.3 (10.8)	43	10.7 (10.3)	-

*One way ANOVA ($p < .000$)

Criteria for exclusion included: systolic blood pressure >130 mmHg; diastolic blood pressure >85 mmHg; body-mass index >25 kg/m2; using medications; smoking; cholesterolaemia; diabetes; and a history of cardiovascular, respiratory, renal, gastrointestinal, hepatic, or systemic disease.

2. 2. 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 from the measurements were calculated.

Heart Rate Variability

A computerized method was used to analyze HRV [6]. The ECG was registered from a bipolar standard I lead. 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 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

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

Intrinsic Heart Rate

Intrinsic heart rate was calculated according to the Rosenblueth-Simeone model [20]. 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 [8]. 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 psycho-physiological research, and to determine whether this parameter could be used for assessment of mental workload and stress.

Data Analysis

Multivariable regression analysis using dummy variable assignment to each group was used to test for significant differences between each group and the referent group for each dependent variable. Gender and age were entered into the models as covariates. A p-value lesser 0.05 was considered statistically significant. The β coefficient for the group effect is interpreted as the difference between the group assessed by that dummy variable and the referent group after adjusting for the age and gender of the subjects.

3.RESULTS

3. 1. 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 univariate analysis of variances. 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**	**Group 5**	**Referent**
Variables	X+/-SD	X+/-SD	X+/-SD	X+/-SD	X+/-SD	X+/-SD
Mean R-R (msec)	798.33 (112.83)	784.46 (113.96)	807.83 (132.25)	749.47 (83.16)	859.53 (132.71)	846.18 (121.8)
Actual Heart rate (beats/min)	76.58 (10.70)	77.56+ (11.31)	75.60 (11.58)	80.88 (9.29)	70.81 (10.52)	72.31 (10.35)
Intrinsic Heart Rate (beats/min)	110.98 (15.51)	112.41 (16.39)	109.57 (16.72)	117.22 (13.46)	102.62 (15.24)	104.79 (15.01)
Ln P_T (ms^2)	1.89 (0.4)	1.73 (0.50)	1.90 (0.42)	1.97 (0.23)	1.93 (0.23)	2.14 (0.42)
Ln P_{THM} (ms^2)	2.31 (0.59)	2.14 (0.56)	1.91 (0.54)	1.66 (0.56)	1.90 (0.57)	2.29 (0.37)
Ln P_{RSA} (ms^2)	1.99 (0.61)	1.72 (0.62)	1.85 (0.57)	1.51 (0.63)	1.88 (0.66)	2.38 (0.45)

Inter-group comparison revealed that workload significantly affected mean R-R interval, HR, HRo, P_T, P_{THM} and P_{RSA}.
Workload was related to a significant increase in mean values of HR and HRo in military pilots of group 2 compared to bank operators and in operators from the Mill factory compared to bank operators and referents. The opposite trend was observed for the mean values of mean R-R interval.
Workload induced a significant decline of mean values of P_{THM} in drivers, Mill factory, and bank operators compared to military pilots of group 1 and in Mill factory operators compared to military pilots of group 2. The same result occurred for Mill factory and bank operators compared to referents.
Workload was associated with a significant decrease of mean values of P_{RSA} in Mill factory operators compared to military pilots of group 1 and bank operators. Mean values of P_{RSA} were significantly decreased in all groups compared to referents.

3. 2. Workload Effect on Autonomic Cardiovascular Control Dependences of Occupational Factors on HRV

The effect of workload on autonomic cardiovascular control was determined by multivariable regression with dummy variable coding for group effects. P_T, P_{THM}, P_{RSA} components are considered to be influenced by autonomic sympathetic and parasympathetic activity [3; 21; 23; 30]. Activity of autonomic cardiovascular control mechanisms as measured by P_T, P_{THM}, and P_{RSA} declines as a function of workload.

Table 3. Significant Differences between Specific Occupational Groups as Compared to Referent Group

	Dependent Variables - β Coefficient (Difference from Referent Group)			
Group	**Ln PRSA**	**Ln PTHM**	**Ln PT**	**Heart Rate**
G1- Military Pilots	-.328	n.s.	-.251	5.50
G2 - Military Pilots	-.472	n.s.	-.336	6.79
G3 - Drivers	-.314	n.s.	n.s.	n.s.
G4 - Mill Operators	-.665	-.414	n.s.	8.71
G5 - Bankers	n.s.	n.s.	n.s.	n.s.

*All significant findings were determined utilizing Multivariable Regression with Dummy Variable Coding for Group effects while controlling for the effects of age and gender.
n.s. – no significant difference between this group and the referent group for this dependent variable

The following differences were observed between specific occupational groups as compared to the referent group:

- Spectral power of the R-R intervals in the Temperature band declined slowly as a function of mental workload of pilots (G2 and G1)
- Spectral power of the R-R intervals in the Traube-Hering-Mayer band declined moderately with an increase of workload of Mill factory operators (G4)
- Spectral power of the R-R interval of the Respiratory Sinus Arrhythmia band declined as a function of workload in military pilots, drivers, and Mill factory operators (G4, G2, G1, G3). A marked decline of the P_{RSA} component was observed as a function of mental workload of Mill factory operators and military pilots (G4, G2).
- In contrast to spectral components of HRV, HR increased progressively as a function of mental and environmental load in Mill operators and military pilots (G4, G2, G1)

4. DISCUSSION

Results of this study indicate that the functional state of the cardiovascular system examined by HR, HRo, and HRV is influenced by mental workload and stress. In Bulgaria in our work environment we cannot separate the effect of these factors as the individuals are exposed to the complex interactions of their work. The same mutual and systematic relation between workload characteristics (overload/underload) and stress determined by catecholamines and psycho-social complaints was observed by Frankenhaeuser and Gardell (1976) [7] in identifying critical factors for human adjustment and health.
We observed that both autonomically controlled cardiovascular parameters (heart rate and spectral components of HRV) change as a function of the complex interaction characterizing our work environment. However, at the same time, in the different groups we observed different functional response patterns depending on the extent of influence of each of the examined cardiovascular measures of level of the cognitive load.
Most sensitive to workload are intrinsic and actual heart rate, mean R-R interval, and the HRV spectral components (P_{THM} and P_{RSA}) in Mill factory operators and military pilots. Mental workload was associated with an increase in the mean values of intrinsic and actual heart rate and a decrease in autonomic activity mediating the spectral components of HRV. These results are consistent with the findings of Grossman and Svebak (1987) [11]; Mulder

(1988) [26]; Kamphuis and Frowein (1985) [18]; Grossman (1992) [10] who reported a decline in the three rhythmic components of HRV under increased mental activity, and with the results of Wilson (1992) [46] and Wilson (1993) [45] who showed that heart rate was sensitive to mental workload. Mean values of age and job tenure were different in studied groups. Heart rate and HRV measures were multiplied by age-transfer coefficients to minimize the age effect. Testing age and job tenure differences between the groups indicated that there were significant differences between these factors between the groups. However these variables were highly correlated and adding job tenure to the models was not significant since the variables (age and job tenure) were "collinear".

In our work environment operators are exposed to mental workload and physical environmental factors and the effect of these factors may be intensified by the impact of social and economic factors pertinent to the post-totalitarian society. These factors affect cognitive functioning and may also affect task performance. Cognitive functions induce and determine defence reactions that could in turn lead either to adaptation or to exhaustion [40]. An earlier stage of the General Adaptation Syndrome is the alarm response (reaction) causing increased of arousal. Prolonged exposure to workload and stress factors could provoke chronic changes in cardiovascular functioning in operators, particularly in Mill factory operators and military pilots. Evidence for this response is the significant increase in mean values of intrinsic and actual heart rate and the decrease in mean values of mean R-R interval in these groups. The most likely reason for the change of intrinsic heart rate is the increased sympathetic activity which mediates slow diastolic depolarization. Chronic sympathetic stimulation causes an increase of heart rate values, although they are moderately elevated.

Auxiliary and simultaneous mechanisms that could induce constant suboptimal functional response equivalent to heart rate acceleration, and which determine its response pattern are decreased parasympathetic activity mediating P_{RSA} and P_{THM}, and decreased baroreceptor modulation of heart rate, assessed by P_{THM}. In our study parasympathetic activity is affected by the following occupational factors: 1. Mental workload of pilots; 2. Workload, noise, and dust in Mill factory operators; 3. Workload, noise, and vibration in drivers. Attenuation or disappearance of RSA under mental workload was confirmed among healthy subjects in another studies [17; 14]. Baroreceptor modulation of heart rate is influenced by occupational factors characteristic for Mill factory operators. Previous studies of the association between adrenergic stimulation related to chronic stress and endothelial injury indicated evidence of the initiation of lesion formation [22] and of the activation of the heart and blood vessels connected with a constant state of visceral-vascular readiness [47] support our thesis of constantly suboptimal functional cardiovascular response patterns under mental workload and stress.

Research investigating the association between RSA, mental workload, and performance postulates complete suppression of RSA in performance at peak capacity with no remaining reserve capacity [17], which may indicate to what extent mental workload is acceptable. Analogous results are found in studies of Hyndman and Gregory (1975) [14] and Jorna (1993) [16]. This basic assumption and the publishded studies allow us to infer that occupational groups most likely affected by eventual performance deterioration are Mill factory operators, military pilots, and drivers. However, according to the definition of Kalsbeek (1993) [17], operators in our study did not reveal complete suppression of RSA under mental workload and stress, and exact determination and assessment of the performance status can be accomplished with an investigation of performance.

In conclusion our results on the cognitive effects of mental workload and stress on operator functional state suggest:

1. In the work environment of the post-totalitarian society we cannot separate the effects of mental workload, environmental, social, and economic factors on operator functional state.
2. Intrinsic and actual heart rate as well as spectral components of HRV change as a function of this complex interaction. Different occupatioal groups revealed different functional response patterns depending on the extent of change in cardiovascular measures. Most sensitive to workload and stress are intrinsic and actual heart rate, and P_{RSA} and P_{THM}. Our results are consistent with the results of Wilson (1992) [46] and Wilson (1993) [45]; Grossman and Svebak (1987) [11] who showed that heart rate was sensitive to mental workload, and with the findings of Grossman (1992) [10]; Mulder (1988) [26]; Kamphuis and Frowein (1986) [18] who reported a decline in the three rhythmic components of HRV under increased mental activity.
3. Work environmental factors affect cognitive functioning. The cognitive effects of prolonged exposure to mental workload and stress induce and may determine constant suboptimal functional response patterns. This pattern we observed in Mill factory operators, military pilots and drivers.
4. Mechanisms that may induce this constant suboptimal functional response pattern are chronic sympathetic stimulation which increases slow diastolic depolarization, decreased parasympathetic activity mediating P_{RSA} and P_{THM} and decreased baroreceptor modulation of heart rate, assessed by P_{THM}.
5. By examining RSA we infer that the occupational groups studied may be affected by eventual performance deterioration. However, according to the definition of Kalsbeek (1993) [17], the operators did not reveal complete suppression of RSA, and exact determination of performance status needs to be determined in future research.

Acknowledgment

Dr. Nikolova thanks to Professor David Shapiro from the Department of Psychiatry and Biobehavioral Sciences, University of California, Los Angeles, USA, for his help.

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