Integrated Estimation of the Effect of Physical Factors on Human Functional State During Mental Work

German A. Suvorov
Ralemma F. Afanasieva
Nataliya S. Mikhailova
Migran A. Babayan
Alexander F. Bobrov
Sergey N. Sokolov

RAMS Institute of Occupational Health, Moscow, Russian Federation

The purpose of this study was to develop a model for an integrated estimation of the functional state of the human organism (FSHO) and an integral estimation of physical factors (PF) for hygienic rating. Tests were performed twice with 3 men in 0.7-clo clothing during 4-hr mental work with 9 combinations of 4 PF: wideband noise (55–83 dB(A)), whole-body vibration (6 Hz, $a_z = 0.2$–1.8 ms^{-2}), air temperature (18–30 °C), and illumination (1, 3, 5 lx). Thermoregulatory, cardiovascular, and psychophysiological reactions and temporary threshold of hearing (TTS$_2$) shifts were studied. For the integral estimation of PF influence on FSHO the model $F(y_1, y_2, ... y_m) = f(x_1, x_2, ... x_n)$ was used, relating both FSHO and PF sets. The most important physiological parameters in creating FSHO are defined and the contribution of individual parameters of FSHO and PF is found.

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Correspondence and requests for reprints should be sent to Sergey N. Sokolov, Russian Academy of Medical Sciences, Institute of Occupational Health, Budennogo prospekt, 31, 105275, Moscow, Russian Federation. E-mail: <SSN2000NS@mail.ru>.

1. INTRODUCTION

Under conditions of industrial activity, human is exposed to the simultaneous influence of various environmental factors. Noise and vibration with unfavourable microclimate (cold or hot) and illumination that do not correspond with standards are common combinations. In a few previous studies an attempt was made to develop methods of an integral estimation of the factors influencing the human organism and to define their importance (Babayan & Denisov, 1991; Bobrov, 1993; Bovenzi, 1986; Dupuis, 1986; Gempe, Pyykko, Stark, & Ilmarinen, 1986; Łuczak, Kurkus-Rozowska, & Sobolewski, 1995; Manninen, 1985, 1986; Spaul, Spear, & Greenleaf, 1986; Vasilieva-Todorova, Dinchikova, Manova, & Chasovinkorova, 1987). There have also been attempts at changing the hygienic requirements for particular factors acting in conjunction with other ones (Babayan & Denisov, 1991; Zvereva, Ratner, Kolganov, & Marienko, 1977).

Modern mathematical methods allow reaching a solution of this hygienic problem from positions of a complex rate setting of factors on the basis of constructing a model reflecting the correlation of a set of human functional state indices with a set of environmental factors (Bobrov, 1990). For multi-factor analysis, it is important to choose a suitable method of statistical analysis and to test data generalization. The traditional approach of using multifactor dispersion analysis and the Fisher criterion for estimating the significance of separate factors and their combination do not allow solving the problem of the prediction of the human functional state on the basis of the values of environmental parameters. In this case, the researcher has to use a few regression models describing the correlation of separate human functional state indices with a combination of linear or nonlinear environmental factors. The number of those equations (dependent on the number of FSHO indices) can be too big for practical use. It would, therefore, be worthwhile to study the multidimension system with multidimension mathematical methods.

This study is to estimate the influence of physical factors (PF; noise, vibration, air temperature, illumination) on the human functional state on the basis of integral functional state of the human organism (FSHO) and PF indices and their correlation.

2. MATERIAL AND METHODS

The study was carried out in a microclimate chamber with the participation of 3 healthy men 20–30 years old, dressed in 0.7-clo thermoinsulated

clothing. For 4 hrs, the men remained in the sitting position and performed mental work consisting of watching a moving object on a display and correcting its movement whenever obstacles appeared. A 4-factor test was planned, including nine PF combinations. The participants were exposed to a simultaneous influence of constant wideband noise (N; 83, 68, 55 dB(A)), whole-body vibration (WBV; 1.8, 1.0, 0.2 ms^{-2} at frequency 6 Hz along the z axis), air temperature (t_a; 30, 24, 18 °C), illumination (I; 5, 3, 1 lx) for 4 hrs with two repetitions. Air humidity was 45% ($\pm$ 5) and air velocity was 0.1 ms^{-1}.

Human heat state, energy losses, hearing sensibility, cardiovascular and respiratory systems, index of stress (IS), and psychophysiological reactions were investigated.

Human heat state (HS) was estimated according to methodical recommendations MR5168-90 (Afanasieva, 1992). Energy losses (Q_{el}) were defined by indirect calorimetry (Spirolit-2). Core temperature (t_r) was measured in the rectum at a depth of 130 mm. Skin temperature (t_s) was measured in nine points of the body surface. Mean skin temperature (t_{ms}) was obtained from local skin temperature (t_s); mean body temperature (t_{mb}) was defined with the use of t_r and t_{ms}:

$$t_{mb} = k \cdot t_r + (1 - k) \cdot t_{ms}, \tag{1}$$

where k is body temperature distributional coefficient calculated by Equation 2:

$$k = 0.037 \cdot TSV + 0.519, \tag{2}$$

where TSV is the human rating of general thermal sensation on a 7-point scale, ranging from 7 for *hot* to 1 for *cold*.

Human body heat storage change (ΔQ_{hs}, kJ kg^{-1}) was defined according to the heat storage level of the human body at relative rest under thermal comfort conditions of $t_r = 37.15$ °C and $t_{ms} = 33.2$ °C. Body water losses (ΔP gh^{-1}) were calculated from the weight change of the human body without clothes. Heat sensation was estimated on a 7-point scale (1–7 standing for *cold*, *cool*, *slightly cool*, *comfortable*, *slightly warm*, *warm*, *hot*, respectively).

The influence of the complex of environmental factors on the organism's hearing function was estimated by test results of the temporary hearing threshold shift during test time at the frequency of 1000 and 4000 Hz for each ear. Heart rate (HR, min^{-1}) was determined by an electrocardiogram recorded throughout the test. Arterial blood pressure was measured by a pneumatopressovasometer. The changes of indices were calculated with

reference to their initial level. The index of stress (*IS*, index of cardial stress) was defined by analysing characteristics of successive time R-R intervals distribution of electrocardiogram by the equation

$$IS = A_{mo}/2\Delta X\,mo,$$

where *mo*—mode, ΔX—mode variation range, A_{mo}—mode amplitude.

Simultaneously with respiration volume and gas interchange analysis, respiratory frequency (*RF*) was studied.

The reactions characterizing the agility of nervous processes, that is, the simple visual motor reaction (*SVMR*) and critical frequency of light flash merging (*CFLFM*) were investigated to estimate the functional state of the central nervous system. The taping test (T_t) was used to estimate the dynamics of the ability to move. Participants were asked to draw quickly (for 60 s) short straight lines on a sheet of paper. The total number of drawn lines was taken into consideration. To estimate attention, an alphanumeric test (*AT*) with Platonov-Schulte tables was used. Measurements of all indices were carried out before the beginning of the test (after 60 min at rest under comfort conditions), during the test (at the end of every hour), and 30 min after its termination.

For the combined estimation of environmental factors, the influence on the human functional state model

$$F(y_1,\ y_2,\ ...\ y_m) = f(x_1,\ x_2,\ ...\ x_n)$$

connecting the total FSHO indices set (y_m) with the total PF indices set (x_n) was used. For the purpose of model construction, canonical correlation analysis was used. It was considered as a generalization of the methods of regression analysis. The canonical correlation model's conformity measure was canonical correlation root value (ρ) reflecting the correlation power of the total independent set (y_m) with the total dependent values set (x_n). The reliability of ρ was estimated by Bartlett's criterion.

The FSHO classification was carried out on the basis of a developed body system reactions index (L_s). Classes were selected by determining dispersion level deviation from the mean value for the total set of the indicated integral index. For formalized estimation of integral FSHO (L_s) and PF (L_r) indices, a probability nomogram built for Bobrov's method was used (Bobrov, 1990).

3. RESULTS

The obtained results allow observing a change of each studied physiological parameter in response to the combined physical factors. In Table 1, the body heat state integral indices and parameters characterizing the energy exchange with the environment are shown. Results indicate a higher rate of metabolism at $t_a = 30\,°C$ ($Q_{el} = 136 \pm 4.1$ W) than at $t_a = 18\,°C$ ($Q_{el} = 107 \pm 3.0$ W, $p < .01$). According to data presented in Table 1, the human heat state depends on the temperature factor, which is specific from the point of view of the activation of thermoregulatory reactions. However, an analysis of the results shows that other physical factors also influence thermoregulatory reactions.

Thus, under the combined influence of noise (83 dB(A)), whole-body vibration ($a = 1.8$ ms^{-2}), and $t_a = 30\,°C$, a decrease of body heat storage, a decrease of thermal sensation vote and water losses take place under lesser energy losses, whereas at $t_a = 18\,°C$ a greater deficit of heat in the body was observed than during exposure to the same ambient temperatures without noise and vibration. A tendency to a decrease of thermal sensation subjective rating was observed under the influence of noise (83 dB) and whole-body vibration of 0.2 ms^{-2}. It should be noted that at $t_a = 30\,°C$, it was accompanied by an increase of heat storage in the organism. This was caused by simultaneous changes of rectal and covered body temperatures in

TABLE 1. Some Human Heat State Indices under Complex Exposition to Physical Factors

	Physical Factors				Heat State Indices			
Test Series	N	WBV	t_a	I	TSV	ΔQ_{hs}	ΔP	Q_{el}
1	55	1.8	30	1	6.4	2.08 ± 0.15	162	128 ± 10.2
2	83	1.8	30	5	4.9	1.76 ± 0.16	90	125 ± 14.7
3	55	0.2	30	1	5.8	2.20 ± 0.13	140	143 ± 11.6
4	83	0.2	30	5	5.3	2.30 ± 0.20	145	145 ± 12.9
5	55	0.2	18	5	3.4	-1.74 ± 0.01	87	118 ± 10.0
6	55	1.8	18	5	3.4	-2.40 ± 0.40	64	114 ± 5.6
7	83	0.2	18	1	2.8	-1.90 ± 0.20	66	101 ± 5.1
8	83	1.8	18	1	2.9	-2.97 ± 0.06	60	97 ± 7.9
9	68	1.0	24	3	4.2	0.63 ± 0.06	62	109 ± 3.6

Notes. N—noise (dB(A)), *WBV*—whole-body vibration (ms^{-2}); t_a—air temperature (°C); *I*—illumination (lx); *TSV*—thermal sensation rating (7—point scale, 1–7—standing for *cold, cool, slightly cool, comfortable, slightly warm, warm, hot*, respectively); ΔQ_{hs}—change of heat storage (kJ kg^{-1}); ΔP—weight change (gh^{-1}); Q_{el}—energy losses (W).

particular by increasing the deep body temperature due to the skin blood vessels constriction and its temperature lowering under the influence of noise. In a cool environment ($t_a = 18\ °C$), noise and whole-body vibration caused the same result expressed ultimately in an increase of heat deficit in the body, that is, in its greater cooling.

The hearing sensitivity was found to depend on ambient temperature. Under noise intensity of 83 dB(A) (vibration 0.2 ms^{-2}), the TTS_2 (temporary threshold of hearing) value at the frequency of 1 kHz slightly decreased at $t_a = 30\ °C$ (to 2.5 dB(A), $p < .05$) whereas at $t_a = 18\ °C$ it increased (to 4.2 dB(A), $p < .05$). Table 2 presents some indices characterizing the changes of the functional state of the participants' cardiovascular system. The results conform to the published information about increased heart rate in a hot environment and a tendency towards bradycardia in a cool environment. According to Table 2, changes of heart rate values were smaller during exposure to 83 dB(A) noise and whole-body vibration with acceleration of 1.8 ms^{-2} or 0.2 ms^{-2} at $t_a = 30\ °C$, compared with the heart rate values during exposure to 55 dB(A) noise. At $t_a = 18\ °C$, bradycardia was less pronounced under the influence of noise of 88 dB(A) and whole-body vibration with acceleration of 1.8 ms^{-2} than at 55 dB(A). This indicates that the changes in heart rate in response to noise and ambient temperature are opposite.

Temperature is the prevailing factor in this study: It defines the degree and direction of heart rate changes. In all series of tests, a bigger increase in blood pressure under the influence of $t_a = 30\ °C$ combined with noise level of 83 dB(A) or whole-body vibration with acceleration of 1.8 ms^{-2} was registered than at $t_a = 18\ °C$. Simultaneous influence of noise and whole-body vibration did not change the blood pressure elevating effect caused by each of these factors separately. Systolic arterial pressure change was most pronounced at $t_a = 18\ °C$ and simultaneous influence of noise of 83 dB(A) and whole-body vibration with acceleration of 1.8 ms^{-2}. At $t_a = 30\ °C$, no influence of these factors on the value of systolic arterial pressure was observed. Perhaps the hypotensive reaction to high air temperature opposed the vasomotor effect observed under the influence of noise and vibration.

Analysis of values characterizing heart activity index of stress (*IS*) indicates a prevailing role of the environment thermal load in its increase. In the series of tests at $t_a = 30\ °C$, these values were in the range of 88–131 units, at $t_a = 18\ °C$ it was 46–99 units. Under the influence of noise (83 dB (A)) and vibration (1.8 ms^{-2}), the value of *IS* was lower (54).

TABLE 2. Some Human Functional State Indices During Test, $\bar{x}$, $n = 12$

Test Series	BPD		BPS		HR		RF	IS	SVMR Δt
	X	Δ	X	Δ	X	Δ			
1	90	15	123	6	82	13	22	88	2.0
2	92	15	118	3	78	5	19	119	6.5
3	92	9	123	5	80	14	16	131	11.4
4	91	16	118	2	80	2	17	103	4.8
5	89	5	126	3	60	−5	17	46	13.8
6	86	6	130	9	65	−8	17	66	0.5
7	91	7	128	10	68	−9	17	53	4.8
8	86	5	130	12	64	−7	16	54	4.4
9	89	10	122	14	71	−9	18	99	2.3

Notes. BPD—blood pressure diastolic; BPS—blood pressure systolic; HR—heart rate; RF—respiratory frequency; SVMR Δt—simple visual motor reaction (%); IS—heart activity stress index per unit: $IS = A_{mo}/2 \cdot \Delta X \cdot mo$; where mo is mode of heart intervals, ΔX is variation range; A_{mo}—amplitude of mode; Δ—value variation with respect to initial one.

However, simple estimation cannot be performed. Perhaps this is connected with tendency toward bradycardia observed under the influence of noise and vibration. At $t_a = 18\,°C$, heart activity IS is essentially lower (by 50%, $p < .01$), at whole-body vibration (1.8 ms^{-2}) this index slightly increases (at 43%, $p < .05$) in comparison with lower vibration (0.2 ms^{-2}). An additional influence of noise on heart activity IS is not essential. Thus obtained data indicate the prevailing influence of temperature load on heart activity IS.

Respiratory frequency (RF) in different series of tests ranged from 16 to 22 min^{-1}. Its highest value was registered in persons exposed to $t_a = 30\,°C$ and whole-body vibration with acceleration of 1.8 ms^{-2}. At $t_a = 18\,°C$, RF was not affected by whole-body vibration. According to data presented in Table 2, the highest increase of the simple visual motor reaction (SVMR) time (18.8%) at the end of the test was observed (under illumination of 5 lx) at $t_a = 18\,°C$, noise (55 dB(A)), and whole-body vibration ($a = 0.2$ ms^{-2}). At $t_a = 30\,°C$ and the same values of noise and whole-body vibration (under illumination of 1 lx), the increase of SVMR was 11.4%. At separate and combined influence of noise (83 dB(A)) and whole-body vibration ($a = 1.8$ ms^{-1}) SVMR time increased to a smaller degree. However, a simple estimation of the effects of noise and of whole-body vibration expressed in an increase of nervous processes agility is not likely to be possible on the basis of the results of this study.

In summary, one can talk about the influence of a combination of physical factors on separate human functional state indices only. However,

from the point of view of the estimation of the total organism's functional state, this is insufficient because not only a different intensity of physiological reactions is observed, but also their different directions. Following are the results of a methodical approach to the definition of the FSHO integral index in correlation with the PF integral index. As it has already been said, it can be solved on the basis of a single multiparameter organism system reaction characteristics (L_s) on a single multiparameter environmental characteristics (L_r). With this $L_s = L_r$. On the basis of the application of the canonical correlation analysis, it was determined that there is close correlation ($\rho = .82$, $p < .05$) between the FSHO and PF sets. The corresponding canonical correlation root model is

$$
\begin{aligned}
-\,0.19 \cdot y_1 &- 0.19 \cdot y_2 - 0.09 \cdot y_3 + 0.06 \cdot y_4 - 0.42 \cdot y_5 - 0.14 \cdot y_6 + \\
&+ 0.13 \cdot y_7 - 0.01 \cdot y_8 - 0.61 \cdot y_9 - 0.76 \cdot y_{10} - 0.61 \cdot y_{11} = \\
&= 0.38 \cdot x_1 + 0.17 \cdot x_2 - 0.93 \cdot x_3 - 0.08 \cdot x_4,
\end{aligned}
\tag{3}
$$

where y_1–y_4—psychophysiological indices (*SVMR*, *CFLFM*, T_t, *AT*); y_5–y_8—cardiorespiratory system indices (heart rate, systolic and diastolic arterial pressure, respiratory frequency); y_9–y_{11}—thermoregulatory reactions indices (Q_{el}, ΔQ_{hs}, *TSV*), x_1–x_4—environmental factors (noise, vibration, air temperature, illumination).

The coefficients preceding the indices characterize factor load and indicate the contribution of each of the initial indices in the revealed multidimension FSHO and PF indices correlation. The model was built for standardized values of the initial indices. Their mean values from the total sample are 0, and the deviation is 1. As it follows from the model, indices $y_9 - y_{11}$ have the greatest weight load characterizing thermoregulatory mechanisms state and y_5 (heart rate), too. This is caused by the greatest influence of the temperature factor (x_3), whose weight load (−0.93) exceeds the weight of x_1 (0.38), x_2 (0.17), and x_4 (0.08). As it is clear from Equation 3, air temperature and noise factor loads have opposite signs, which conforms with the described earlier different character of physiological reactions number change under their influence.

Classification and prediction of a human's FSHO when working under unfavourable conditions is an important practical task. FSHO classification was carried out on the basis of an organism system reactions index (L_s). Classes were picked out by determining the deviation of dispersion levels from the mean value for the total set of indicated integral indices. Three

signal classes (P_1, P_2, P_3) for FSHO and PF were chosen. The values of the initial indices corresponding to them are shown in Tables 3 and 4.

The PF indices (Table 3) in comparison with the values of the FSHO indices (Table 4) allow the second class to attribute to the optimum that conforms particularly with optimal human heat state indices (Afanasieva, 1992).

TABLE 3.   Initial Environmental Physical Factors Different Class Indices

Class	Physical Factors				
	N	WBV	t_a	I	L_s
P_1	64.88	0.86	30.0	2.41	−1.2000
P_2	67.70	1.00	24.0	3.44	−0.0465
P_3	75.50	1.13	18.6	2.05	1.2280

Notes. N—noise (dB(A)), *WBV*—whole-body vibration (ms^{-2}), t_a—air temperature (°C), *I*—illumination (lx), L_s—integral index.

TABLE 4.   Initial Human Functional State Different Class Indices

Class	Q_{el}	TSV	ΔQ_{hs}	HR	BPD	BPS	RF	SVMR	AT
P_1	84	5.4	1.94	79	91	124	17	265	117
P_2	68	4.2	0.57	75	84	122	18	242	129
P_3	53	3.1	−0.94	67	84	126	16	234	124

Notes. Q_{el}—energy losses (Wm^{-2}); *TSV*—thermal sensation rating (7-point scale, 1–7 standing for *cold*, *cool*, *slightly cool*, *comfortable*, *slightly warm*, *warm*, *hot*, respectively); ΔQ_{hs}—change of heat storage (kJ kg^{-1}); *BPD*—blood pressure diastolic (mmHg); *BPS*—blood pressure systolic (mmHg); *HR*—heart rate (min^{-1}); *RF*—respiratory frequency (min^{-1}); *SVMR*—simple visual motor reaction (ms); *AT*—alphanumeric test.

The changes of the first and third class indices can characterize the upper and lower limit PF permissible values and FSHO—which depends on them—as permissible. For formalized estimation of FSHO and PF, a probability nomogram (Figures 1, 2) was worked out. That is why FSHO (L_s) and PF (L_r) integral indices calculation formulas were reduced to nonstandardized initial indices:

$$L_s = 6.907 - 0.0175 \cdot Q_{el} - 0.115 \cdot TSV - 1.321 \cdot \Delta Q_{hs} + 0.0114 \cdot BPD +$$
$$+ \; 0.00956 \cdot BPS - 0.0316 \cdot HR + 0.00909 \cdot RF - 0.0144 \cdot SVMR -$$
$$- \; 0.0792 \cdot CFLFM + 0.00266 \cdot T_t + 0.00384 \cdot AT, \qquad (4)$$

where Q_{el}—energy losses, *TSV*—thermal sensation rating, ΔQ_{hs}—change of heat storage, *BPD*—diastolic blood pressure, *BPS*—systolic blood pressure,

HR—heart rate, *RF*—respiratory frequency, *SVMR*—simple visual motor reaction, *CFLFM*—critical frequency of light flash merging, T_t—taping test, *AT*—alphanumeric test.

$$L_r = 2.509 + 0.025 \bullet N + 0.252 \bullet WBV - 0.182 \bullet t_a - 0.0465 \bullet l, \qquad (5)$$

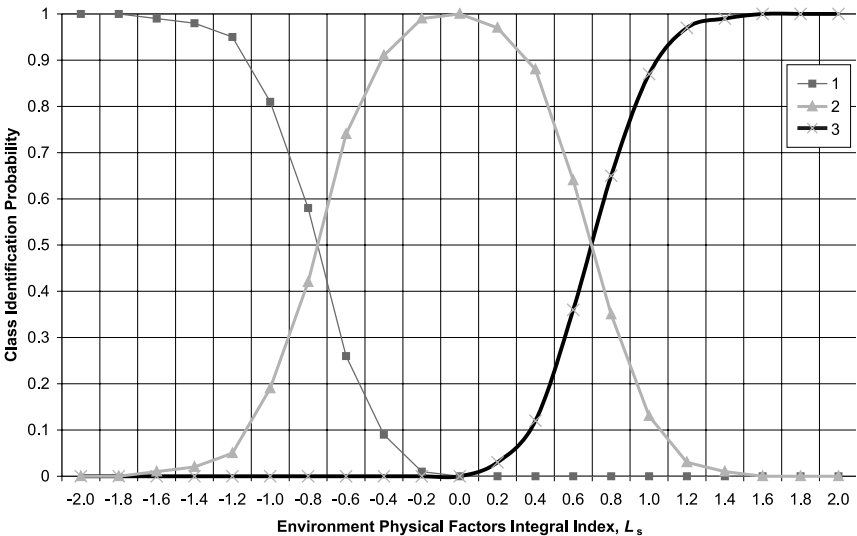where *N*—noise, *WBV*—whole-body vibration, t_a—air temperature, *l*—illumination.

Figure 1. Human functional state forecast probability nomogram under unfavorable conditions.
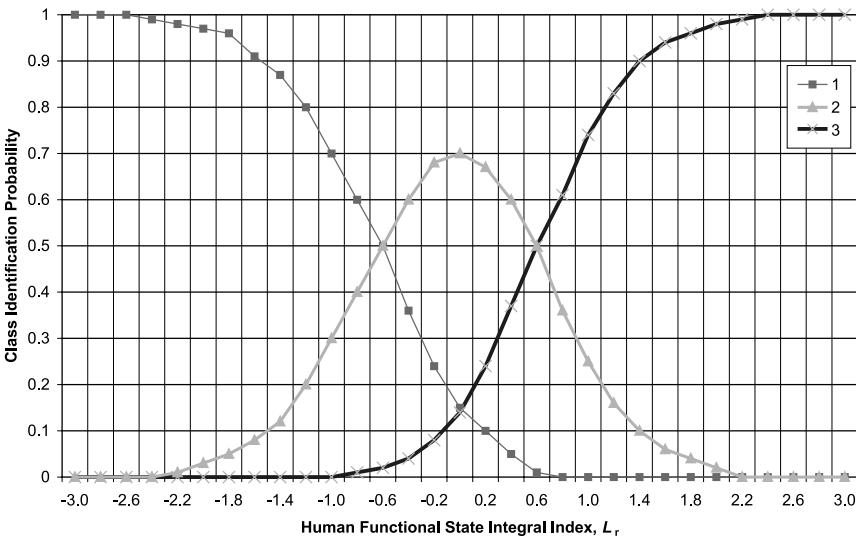*Notes.* 1, 2, 3—classes of the functional state of the human organism.

Figure 2. Human functional state forecast probability nomogram by environment factors.
Notes. 1, 2, 3—classes of the functional state of the human organism.

The functional state estimation rule consists of the following: The absolute values of the FSHO initial indices are substituted in Equation 2 and the integral index (L_s) is calculated. Its value is marked on the abscissa axis (Figure 1). From the obtained point, it is necessary to raise a perpendicular line to the crossing with class (P_1, P_2, P_3) limits. Crossing points project to the ordinate axis, by which the identification probability of each of the three FSHO classes is defined. The solution is reached by the greatest value of class identification probability.

For example, if $L_s = -1$ units, the identification probability of FSHO level corresponding upper limit of a permissible one (P_1) is 0.8 and an optimal one (P_2) is 0.2. As maximal probability corresponds to class P_1, one decides that this human's (or group's) functional state corresponds to the upper limit of the permissible one during a work shift (Afanasieva, 1992). Thus offered FSHO estimation method allows calculating diffuse limits between the functional state of neighbouring classes. The human functional state prediction can also be done by the values of environmental factors (Figure 2). The difference of this probability nomogram from the one shown in Figure 1 is that on the abscissa axis environment estimation integral index value (L_r) calculated by Equation 5 is drawn.

The present probability nomogram allows predicting the influence of human functional state exposed to combined environmental factors without conducting corresponding studies. Undoubtedly, the indirect prediction lowers the precision of the FSHO identification that is reflected in diffuse limits between the increase of neighbouring classes. However, it essentially simplifies the solution of the practical task.

For example, at a workplace noise of 75 dB(A), vibration of 0.8 ms^{-2}, air temperature of 26 °C, and illumination of 2 lx are registered. The human functional state class should be defined.

According to Equation 5, L_r is 0.24 units. In Figure 2, we define that the organism functional state can belong to class 2 with the probability of 0.65, to class 1 with the probability of 0.25, and to class 3 with the probability of 0.1.

According to Equation 5, one can also solve other tasks, particularly to what degree one can change FSHO at the expense of a change of the levels of environmental physical factors. For example, in the situation just described, it is not possible to optimize air temperature. To what degree will FSHO improve if noise level decreases to 55 dB(A), whole-body vibration decreases to 0.2 ms^{-2}, illumination decreases to 3 lx? By solving Equation 5 we obtain that L_r is 0.94 unit. This means that the functional state with the

probability of 0.70 can belong to class 2, with the probability of 0.10 it can belong to class 1, and with the probability of 0.10 it can belong to class 3. Thus, FSHO will improve a little but a decrease in air temperature is also necessary for its optimization. Undoubtedly, the presented equations for an integral estimation of the human functional state, including environmental factors indices, correspond to a concrete situation. The mathematical method used can also be used for solving wider hygienic tasks.

4. CONCLUSIONS

The experimental studies and their mathematical statistical analysis allow the following conclusions to be drawn with reference to estimating the effect of the complex of physical factors on a human performing mental work.

- Environmental physical factors (noise, whole-body vibration, temperature, illumination) can cause differently directed reactions of various body functional systems. Combined PF influence dependent on individual levels can intensify or weaken body responses. The contribution of the environmental physical factors to the human functional state is not equal.
- Complex estimation of environmental physical factors (noise, whole-body vibration, air temperature, illumination) can be done on the basis of single multiparameter characteristics of the systematic reaction of the organism.
- On the basis of probability nomograms, one can predict the organism's functional state by its integral index (L_s) and environmental factor load integral index (L_r) including diffuse limits between the neighbouring classes of the human functional state. Data can be used for solving hygienic tasks related to the estimation of a complex of physical factors.

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