Multimodal Recognition of the Stress when Performing Cognitive Tasks under Limited Time Conditions

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Abstract. In the usual human cognitive performance, the speed of the human-computer interaction is not critical, but in emergent technologies and in a high stream of information in a learning process, a human (learner) ability to process teaching tasks can be limited by the human abilities or lead to this human's stress as a physiological "cost" of his/her successful performance. The goal of the paper is to carry out the comparison analysis of the speed and reliability of cognitive activity by subjects performing computer tasks at a free and fixed pace, considering the physiological "cost" of such activities to reveal potential preliminary markers of stress. We have studied 4 group of indices of subjects' cognitive test performance: 1) operational - test performance including direct indices (rate of tasks solving, reliability) and their secondary indices including general productivity; 2) subjective test indices before and after test performance; 3) physiological support of activity by indices of the cardiovascular system; 4) indices of electropuncture diagnostics. Besides, to account external factors of possible influence on a human cognitive work, we used indices of the solar wind and geomagnetic field. The time limitations make a human more sensitive to external physical factors and influence his psychological state in addition to physiological regulation that can be considered as a stress condition of activity. This result has confirmed our guess that multimodal description is more effective to reveal a stress during cognitive activity of a simple nature.

Keywords: Cognitive Performance, Stress, Multymodality.

1 Introduction

The Future of Growth Report 2024 presented by The World Economic Forum in Davos (January 2024) has shown that the future of growth can be grounded by “four areas essential to driving more balanced growth: innovation, inclusion, environmental sustainability and systemic resilience” [1, p.9]. Those areas can be structured in subsystems and the high rank of them is a “Talent ecosystem”. That notion was in line with outcomes of the WEF over the last 5 years.

It means that lifelong learning needs new skills and continues re-skilling [2], set new requirements to learners and workforce, especially because of appearance of the hybrid workforce as a new trend over last year’s [3]. As a result, new requirements to modern schools have appeared [4] and are needed in both education [5] and research [6]. In addition, the digital transformation of the society is accompanied by the ICT evolution in all areas of a human life and activity [7].

A particularly striking explosion of interest in the last few years has been observed in the field of immersive technologies and artificial intelligence, both in education and in other areas. This led to a revision of the Milgram and Kishino's reality-virtuality (RV) continuum [8] and rethinking the ways and forms of human-Artificial Intelligence interaction [9]. To date, the RV continuum is considered more as unending and is often described as Extended Reality (XR). According to the authors of [10], today’s view of the synthetic environment points to the increasing “role of XR in spatial perception, cognition, and behaviour and *vice versa*. XR offers a plethora of opportunities to reveal new or unexplored dimensions of human interaction with environments”. At the same time, user states in extended reality media experiences are still a very difficult problem without a clear solution and thus heavily worked upon [11].

New learning tools and technologies give new opportunities of learning. In particular, a new direction began to take shape more clearly - VARK, four sensory modalities (Visual, Aural, Read/write, and Kinesthetic) that are used for learning information and that can be associated with the students’ and teachers’ experiences [12]. It can be especially effective in the synthetic learning environment that extends a learner opportunity to use more sensory channels to get new information [13]. The methodological and instrumental basis for this direction is developing and improving very actively, because life is multimodal, and there are seldom instances where one mode is used or is sufficient [14]. Respectively, a multimodal learning looks like more effective. The highest popularity such an approach demonstrates by language teachers and researchers [15], but in general, it could be appropriate in other areas where flexibility of education can be provided, and the learning style can be essential and productive [16].

Multimodal teaching, learning, and training allows to increase motivation and efficiency of the learning process. But on the other hand, this increases the tension of the body’s regulatory systems, involving more of them in the physiological support of learning activities and “imposing” a certain pace of information exchange between the learning environment and the learner. Although according to the authors [17], there is no evidence that associations between adolescents’ digital technology engagement and mental health problems have increased, possible clinical consequences of innovative technologies should be evaluated *before* their implementation into the education process. Significant, but not always studied in innovative tools, functional deviations in the functioning of physiological support can manifest themselves at a subthreshold level. According to study of physiological response of volunteers' performed cognitive tests with different time limitations for a task [18], the analysis of the lipid metabolism have shown different changes in ratio of saturated and polyunsaturated fatty acids classifying subjects in 3 groups: high, medium and low adaptive ability. That finding can be used as preliminary sickness' indicator in conditions of regular repetitive workload in digital environment and a low stress associated with the cognitive task performance. It has been revealed that such an effect can be described for different subjects by different physiological indices and with different level of accuracy of assessment.

The **goal** of article is to carry out the comparison analysis of the speed and reliability of cognitive activity by subjects performing computer tasks at a free and fixed pace, considering the physiological "cost" of such activities to reveal potential preliminary markers of stress. We consider the “stress”, but not the “distress” (after H.Selye).

2 Method

The research method used in this study was the development of the method used in our previous research of the psychophysiological maintenance of operator cognitive performance [19] and in applications to study learners' performance as operator-researchers [20]. The current modifications of the research method relate to the test performance and data analysis to achieve the research goal.

As in our previous research [20], 5 weeks experimental research was based on the use of a computer system to monitor the cognitive activity of subjects (15 MSc and PhD students, males). The survey includes test task performance (2 types of logical tasks, and test for functional mobility of nervous processes' assessment), blood pressure and heart rate (heart rate HR and blood pressure (systolic ADs, diastolic Add, by means of the digital blood pressure monitor Model LD11) every 20 minutes during the test performance, as well as electropuncture diagnostics (EPD) by Nakatani method (together with Mygal and Protasenko) was conducted after the test session for each subject [21].

The adjusted tests block included:

Self-assessment test T4. The subjective state assessment of subjects by means of the reduced variant of the test “General_state - Activity – Mood” (GsAM), test T4, at the beginning and at the ending of the test session (the indices of mood *mood*, serviceability *FfD*, attention *atten*, anxiety *anxiety*) prior to the beginning (index "0") estimated and upon finishing the tests performance.

Numbers permutation test (combinatorial) in ascending order. The test material: a sequence of numbers (from 0 to 9) which were not repeated and placed in a random order; the task was to rearrange the numbers in ascending order in a few steps, on each one could only change 2 adjacent numbers. Time for every task performance was free during the test session (the next task appeared just after entering the answer), "auto"-pace (test T6) or fixed one (time for every task was limited and fixed in each session, calculated as an averaged time plus 25%, after the training session, test T5). The time (Tl) and accuracy of the task performance were measured.

Duration of every test session was 180 minutes, 5 sessions (the first one was training to adapt to the cognitive test and physiological indices measurement) were organized 1 time per week, at the same day of week and the same day time to eliminate infradian and circadian rhythms. Test T5 was used in the experiment sessions 3, 4 and 6 (E3…E6), test T6 was used in the session E5.

To check an influence of the external physical factors on the cognitive task performance the solar activity was studied as external factor possibly impacting a human performance. The data on influence of solar activity on a human health and some physiological systems are known, however results of study of cognitive activity associating with heliophysic parameters in different activities and different groups of subjects are known not enough in the scientific literature to date. In our preliminary pilot research the precise connection between effectiveness of operator activity and parameters of a solar wind (SW) was revealed. With the purpose to study this phenomenon we registered indices of proton component of a solar wind - velocity SWsp (km/s) and density SWden (proton/sм^3) on the data from Internet site NASA [22], as well as parameters of the geomagnetic field (GMF) - planetary index Ks, index of "equivalent amplitude" A, as well as Wolf number of the solar spots.

Because the study involved human subjects, all subjects signed the informed consent of participants, their personal data were excluded from the database of research, their participation in this research was coordinated and approved by the university authority. In addition, it has been acquired the approval of the National Committee for bioethics of Ukraine in order to conduct the study.

3 Results and discussion

The focus of our research is revealing some potential markers of stress at preliminary stages before the clinical changes of a human organism. It is possible to do if measuring functional changes in physiological indices as under influence of workload and external factors accounting "starting" (in the beginning of the cognitive performance) and the current functional state during work (test task performance in our study).

It is well-known that a human activity is modulated by a hierarchy of rhythms both internal and external. And their constellation influence reliability and efficiency of a human performance in specific elements and in general. The most known rhythms are circadian, infradian and lunar once. To eliminate their possible influence. Our research was carried out in the same day of a week, the same time of a day and one time per week for every subject to study a human performance and its physiological "cost" in similar conditions. The duration of every experimental session was 3 hours and the dynamics of the test performance has been assessed by way of averaged data stored every 20 minutes smoothing out the effects of catecholamines (most of which have a period of 3.5 to 15 minutes) and averaging data of the whole test time.

One more important feature of our research is to compare free and fixed pace of tasks to be solved by way to adjust fixed time to every subject: an individual fixed “average” time was calculated by results of the first, training, session with the free pace. Because all subjects were well-motivated, they were in equal conditions and were compared not with one another, but with their inherent parameters of activity.

As it was revealed in our previous research, the analysis of this study has confirmed that time of tasks performance had individual dynamics and average time (M3, M4 and M5 respectively to experiments in the number of the research week) fluctuated and differed in the same fixed tempo from one week to another (see Fig.1). Not only average level of tasks’ time performance, but their inner regularity differed.

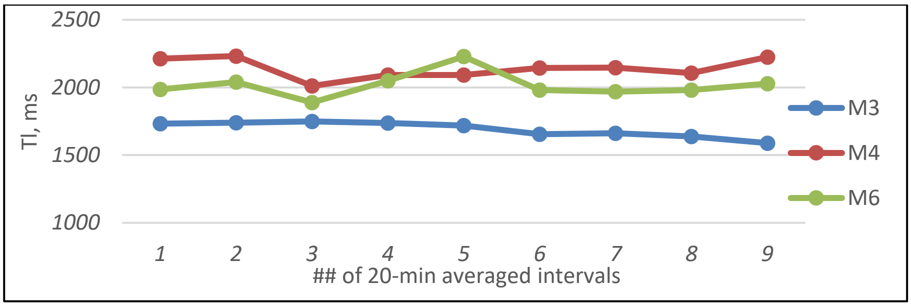

Fig. 1. An example of the dynamics of the tasks’ performance time, one subject.

3.1 Test performance productivity

As it is possible to see from this example, variation of the task time performance can vary significantly from day to day for each person. One of questions in our study was whether a general tendency can be in the whole group of subjects, if to compare experiments’ results in a month and the test tempo. The study was organized in such a way that all subjects underwent the next experiment in the same week. In other words, each number of the experiment corresponded to the same phase of the month.

One can see from the Table 1 that averaged time of the tasks performance (Tl) in the column 2 does not differ between experiments with the fixed pace (experiments E3, E4 and E6). But Tl in the experiment with free pace (E5) differs significantly, and the coefficient of variation (cv Tl) is twice higher than in fixed pace’ experiments.

Table 1. Averaged results of tests performance by experiments.

# Experiment	Tl, s	cv Tl, %	W	UTR
E3	2.62	53	0.36	0.52
E4	2.61	60	0.45	0.45
E5	3.56	123	0.31	1.0
E6	2.50	66	0.50	0.39

It is expected that reliability and time of task performance can depends on the individual style of work. To avoid this difficulty, we calculated the productivity factor to accounting efficiency of the test performance as the ratio of reliability (ratio of correct solved tasks to the whole numbers) to Tl : W = R/Tl*1000. This factor demonstrated a good usefulness in our previous research [20]. According to data in the Table 1, the productivity W5 in the test 5 does not differ from W3…W6 so significantly as Tl. It can be explained by the fact that the reliability in tests E3, E4 and E6 is lower than in E5 (in average, 0.87 *vs*. 0.98).

According to this finding, we can suppose that the fixed tempo (TT) of tasks performance mobilized subjects to work with some greater "tension" putting in more effort, though their fixed tempo was quite similar to their own tempo.

What could have further usefulness is a study what part of the "window" (exposition time) for the task performance was used by subjects actually and whether they could control their time for every task without loss of reliability. To answer that question, we calculated **u**seful **t**ime utilization **r**ate (UTR) as a factor UTR = Tl / TT.

The Table 1 demonstrates that when subjects used more time and UTR was 0.52 (i.e., they used 52 % of time available for task solution), their productivity was lower than in other cases. In fixed pace test, they used 100% of time, because the next task appeared just after entering the answer. One can assume that the lower productivity is a result of lack of a time reserve and lower reliability (it was the lowest in the experiment E3).

3.2 Physiological support of the test performance

The physiological support of activity had an even more pronounced individual character by indices of blood pressure systolic (BPs) and diastolic (BPd) that was natural and well known from scientific publications. Their averaging does not have clinical reason but can be informative for analysis of the test performance changes and appropriate physiological support. The Fig.2 demonstrates the dynamics of the systolic blood pressure (subjects averaged for 20-minutes intervals continuously, mmHg) by experiments sessions (E3, E4 and E6 as above).

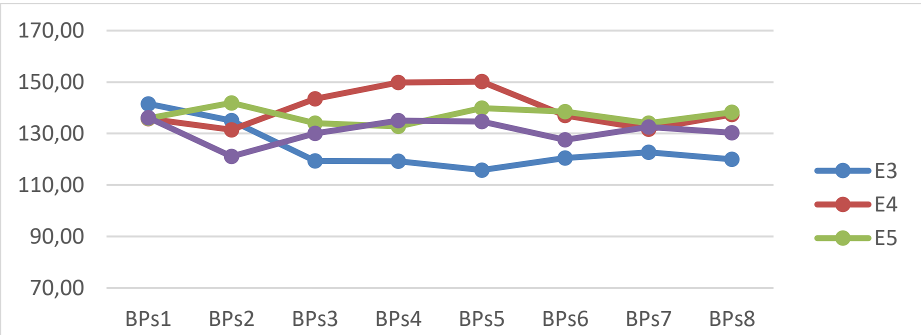

Fig. 2. Changes of BPs (subjects averaged) over the test session.

As one could expect, the main trends exist independently on inter-individual variation and differ for all three fixed pace tests, on one side, and free pace, on another one. The fixed pace tests are accompanied by clear decries of BPs in the beginning of the test performance (first 20 minutes) and its differed levels till the end of the second hour (measurement in point # 6). Afterwards, BPs has stabilized till the end of the session. At the same time, free tempo (experiment E5) is accompanied by some 1-hour (three 20-minute intervals) fluctuations of the BPs. This can be explained by a higher efforts of the subjects' mental work under "pressure" of the fixed time for tasks and needs of some additional physiological support of the neurohumoral system. The experiment E3 as the first one in the sessions' series required additional emotional mobilization of the subjects at the beginning of the research (an element of anticipation of a new type of activity), since they were all highly motivated and responsible.

But the diastolic blood pressure BPd has dynamics closer to free pace test in experiment E6 than in E3 and E4 (see Fig.3). It can be assumed that this type of cognitive activity has become more common, and the regulation of the diastolic component of blood pressure may have a slightly different character than the systolic component. In our earlier studies of the influence of heliophysical factors on operator-type's cognitive activity, it was revealed that it was diastolic blood pressure that was more sensitive to such influence [23].

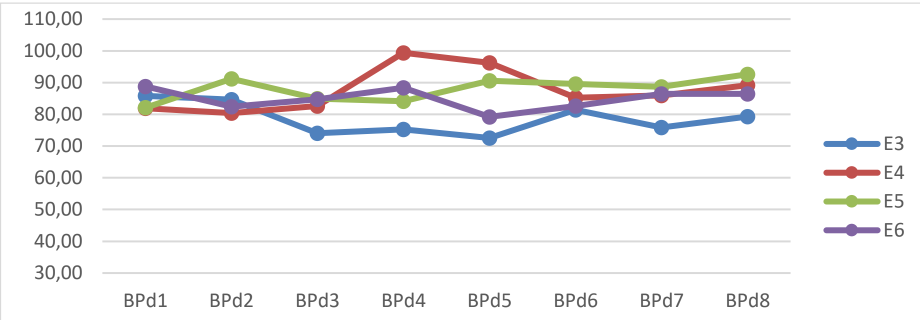

Fig. 3. Changes of the diastolic blood pressure (subjects averaged) over the test session.

It is necessary to note that the heart rate in all experiments has very similar dynamics and decreasing evenly from the start to the finish of test sessions from approximately 88 bit per minute to 70 bits.

Thus, a preliminary conclusion can be made that the cardiac respiratory system as a whole can carry information about the manifestation of stress changes, but its indicators change in different directions.

According to our previous research, electropuncture diagnostics' (EPD) indices can be informative in relation to some stress changes during cognitive work [20].

However, it is necessary to note that EPD is used in clinical goals, as a rule. The questions of its application for functional implementation is still under consideration, especially because of different tools and methods of measurement.

Since in 1950, the Japanese physician Y. Nakatani described the method of electropuncture diagnostics of the functional state of meridians, based on the measurement of electrocutaneous resistance (ECR) at representative acupuncture points, this approach has gained many supporters both for clinical purposes and as well as general diagnostics of the body's condition [24]. We have found in our joint research that EPD by Y. Nakatani method could be informative tool to study external influences and appearance of the stress during cognitive activity. Colleagues, G.Mygal and O.Protasenko, developed that technique in direction to use skin capacity indicators in wider applications [21]. In this research, we used more traditional approach, measurement of skin resistance indicators, to analyze appearance of signs of stress during 3-hour cognitive activity (classical 12-points measurements in representative meridians left Rl and right Rp).

If to compare the left (before the test session beginning, index "0") and right (after the test performance finishing, index "1") histograms at the Fig. 4, one can see some decries of points' resistance of many meridians.

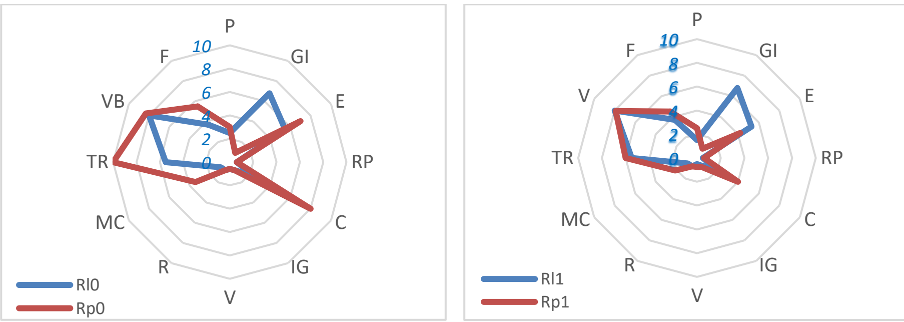

Fig. 4. Changes of skin resistance in acupuncture points by Y.Nakatani method before test performance (left) and afterwards (right). Example of one subject in E6.

But in the experiment with free pace of task performance (see Fig.5), associated changes in the skin resistance have the opposite trend and resistance increased after the test performance, and its structure (the subjects' EPD 'portrait') is significantly different in comparison with the fixed pace tasks.

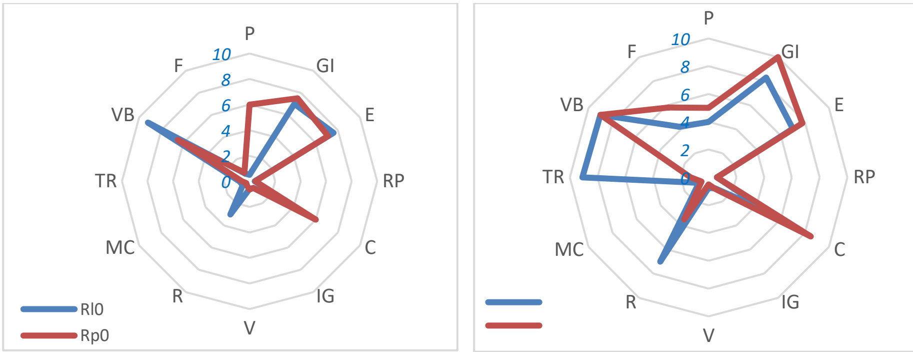

Fig. 5. Changes of skin resistance in acupuncture points by Y.Nakatani method before test performance (left) and afterwards (right). Example of the same subject in E5.

According to Nakatani, any changes in the internal organs are certainly reflected in the skin. It follows that the ryodoraku (meridians) act as sensitive indicators to these changes, signaling danger and, to a certain extent, its extent. Later it was recognized that the phenomenon of ryodoraku is noted not only in connection with the disease of the organ, but also reflects its physiological changes, therefore they began to distinguish between "pathological" and "physiological" ryodoraku. Some authors explain this phenomenon by the viscerocutaneous sympathetic reflex.

The physiological mechanisms of such changes are not the subject of study in this article; we are only looking for objective indicators that could be used in assessing the occurrence of a certain stress when a human performs cognitive tasks (even simple) with the computer and has more or less continuous interaction with it.

Though averaging of all subjects' physiological indices does not have ф semantic interpretation, practical usefulness of the EPD indices could be useful at pragmatic level, if some indices could have a general trend. So, we use not prompt meridians' indices (they differ from one subject to another), bur asymmetry factor AF (left-right hands and feet). It has been revealed that AF >1 in all experiments excluding E3 (as in BPd). After experiments, all AF have normalized and approached 1, the higher balance was achieved in E5 (1.03). The biggest changes during the test sessions in the resistance value were registered for the right hand (all subjects used right-hand mouse).

It is possible to note that changes under influence of the cognitive test performance during 3 hours in physiological response (by all meridians) were registered, as well as a difference in response to fixed and free tempo of workload in tests.

As a result, it is possible to consider some indices of the physiological support as indicators of the stress, but their predictive possibilities when using separately are questionable.

3.3 Multimodal recognition of stress in test performance

We have studied 4 group of indices of subjects' cognitive test performance: 1) operational - test performance including direct indices (rate of tasks solving, reliability) and their secondary indices including general productivity; 2) subjective test indices before and after test performance (the index “anxiety” decreased in E5 and E6 for 1/3 of subjects but increased for almost all subjects in E3 and E4); 3) physiological support of activity by indices of the cardiovascular system; 4) indices of electropuncture diagnostics. Besides, to account external factors of possible influence on a human cognitive work, we registered indices of the solar wind and geomagnetic field (described in p.2) that were informative in relation to cognition after our previous research.

No one group of indices could not be enough strong indicator differentiated work with time limitations and without them. We believe that multimodal assessment could be more informative even with reduced number of indices but when they have synergetic effect. To confirm or to reject this notion, we used multiple regression analysis with the forward stepwise procedure (formal, used only mathematical criteria without participation of researchers) selecting the most informative index at every step. The criterial (outcome) index was the subject’s productivity in the cognitive test performance. It was assessed by the model built by appropriate formal selection of indices from other group of indices.

Models for the index W were built separately for the test with the fixed pace (with some time “tension”) and for auto (free) pace, accordingly, Wf and Wa.

The “optimal” Wf model included such indices: BPs2, Rl1, BPd6, BPs7, Ks and “rest” (subjective index of the feeling “rest – fatigue”). The structure of this model represented all group of indices: cardiovascular system (blood pressure at the 2^{nd}, 6^{th} and 7^{th} 20-minute intervals); EPD index (skin resistance of the left part of meridians after the test performance); external influence (Earth's magnetic field’s index Ks). The multiple correlation coefficient was $R = 0.71$, $p \leq 0.001$.

The “optimal” Wa model differ by its indices structure and included: BPs9, HR5, Rl1-Rl0 and BPd8 ($R = 0.98$, $p \leq 0.001$). This model could describe the high productivity in the test performance by only physiological indices (blood pressure and EPD as changes in the skin resistance in left meridians over the test session).

The structure of models Wf (model for a normally stressed cognitive performance) and Wa (stressless performance) differ and demonstrated that the stress involves more complex mechanisms of regulation and depends on both internal and external factors.

4 Conclusion

These results argue that cognitive activity of such a type can be described only with physiological parameters in conditions of free pace (natural and comfort for a human) of the tasks stream. But the time limitations make a human more sensitive to external physical factors and influence his psychological state in addition to physiological regulation that can be considered as a stress condition of activity.

This result has confirmed our guess that multimodal description is more effective to reveal a stress during cognitive activity of a simple nature.

The results can be applied to optimize a human and digital system interaction accounting a human cognitive and psychophysiological limitations in interaction pace. The optimization goal can be to adjust their interaction pace to avoid stress appearance and to achieve maximal general performance in short- and long-term perspective by using models for prediction of student ability to effective learning [25], as well as in designing working environment as an element of the ensuring automated systems [26].

Further research: study a possible cumulative effect and long-term consequences of repetitive and/or prolonged even “low” stress when working in the digital environment.

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