PICTORIAL COGNITIVE TASK RESOLUTION AND EXPIRED MINUTE VENTILATION, OXYGEN CONSUMPTION, CARBON DIOXIDE PRODUCTION AND HEART RATE

Josef Petrek

Department of Physiology, Faculty of Medicine and Dentistry, Palacky University, Olomouc, Czech Republic
e-mail: feso@tunw.upol.cz

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Aims: To assess the impact of cognitive task solving on respiratory and cardiovascular parameters.

Methods: The ML870B80 Exercise Physiology System was used to record concurrently with EEG, the cardio-respiratory and metabolic functions of subjects during cognitive activity. The Expired Minute Ventilation (V_E), Oxygen Consumption (V_{O_2}), Carbon Dioxide Production (V_{CO_2}) and Average Heart Rate (BPM) were ascertained for four periods: (1) rest or starting period, (2) reference period, (3) cognitive task solving period and (4) recovery period. Each period was defined by the type of presented visual stimuli and by the prearranged cognitive activity related to visual stimuli. The personality traits of participants were also determined.

Results: The momentary functional state of subject's brain (i.e. the period of the experiment) determined the average values of all measured parameters. During the cognitive task solving period the average V_E , V_{O_2} and V_{CO_2} reached the lowest values while the HR behaved reversely – it was the highest in the cognitive task solving period. Further, the average V_E , V_{CO_2} and HR values but not V_{O_2} value differed significantly from average values for the same variable measured in the rest period.

Conclusion: The changes in respiratory variables during the cognitive task solving period predicate the whole-body metabolic rate rather than the energy metabolism of the brain alone. However, the heart rate related to some personality traits of the subject has a tighter relation to brain's energy metabolic rate during the cognitive task solving – it affects the oxygen supply of the brain.

INTRODUCTION

The brain makes an ongoing energy demand. The mean level of energy required by the brain is very high under resting conditions and it increases markedly during exercise. According to Guyton and Hall⁹, the brain metabolism per unit mass of tissue is about 7.5 times the average metabolism in non-nervous tissues. This means that the brain, like the other organs in the human body, needs more glucose, oxygen and other essentials under demanding conditions. The energy requirements of different areas of the brain also fluctuate over time and the delivery of oxygen and glucose change accordingly. It should be emphasized here that experimental descriptions of the coupling between demand and supply in laboratory animals was provided by Roy and Sherrington¹⁹ over a century ago. According to them, “the brain possesses an intrinsic mechanism by which its vascular supply can be varied locally in correspondence with local variations of functional activity”.

A precise quantitative assessment of the coupling between neural activity and changes in regional blood flow and/or cerebral metabolic rate of oxygen consumption or evaluation of the dynamics of other metabolic intermediates were only possible after the introduction of modern

non-invasive functional brain imaging techniques*. These new imaging techniques gave researchers interested in the function of the brain a suitable tool enabling them to examine the neurobiological correlates of human behaviours. This is exemplified by the increasing number of papers published in the past several years^{see e.g. 6-8, 10, 14, 15, 20-23}.

Much of this work demonstrated that information processing in the human brain involves a concurrent activity of multiple spatially distributed cortical regions that participate in various information processing operations. They also showed that changes in the cellular activity of the brain are invariably accompanied by metabolic changes, especially changes in local blood flow, in oxygen

* Signals detected with functional brain imaging techniques (see Magistretti and Pellerin¹³) are based on the coupling between neuronal activity and energy metabolism. Positron emission tomography signals detect blood flow, oxygen consumption and glucose utilization associated with neuronal activity. The degree of blood oxygenation is thought to contribute to the signal detected with functional magnetic resonance imaging, whereas magnetic resonance spectroscopy identifies the spatiotemporal pattern of activity-dependent appearance of metabolic intermediates, such as glucose or lactate. Despite the technological sophistication of these brain imaging techniques, the precise mechanism and cell types involved in coupling and in generating metabolic signals are still debated.

Table 1. Correlation coefficients describing the relationship between the FPI score of twelve personality traits and the average values of V_E , HR, V_{O_2} and V_{CO_2} calculated in different periods of the experiment.

Variable	Correlations: FPI vs. VE											
	Bold numbers on a grey background – correlations are significant at $p < .05$											
	N = 13											
	FPI 1	FPI 2	FPI 3	FPI 4	FPI 5	FPI 6	FPI 7	FPI 8	FPI 9	E	N	M
1VE	0,36	0,20	0,68	0,14	-0,81	-0,49	0,04	0,72	0,28	-0,69	0,51	-0,31
2VE	-0,09	-0,49	-0,46	-0,08	0,50	0,44	-0,01	-0,21	-0,47	0,04	-0,58	-0,09
3VE	0,45	0,11	0,64	0,27	-0,64	-0,46	-0,02	0,53	0,10	-0,57	0,49	-0,14
4VE	0,24	-0,16	0,48	0,15	-0,61	-0,51	-0,01	0,65	0,24	-0,68	0,29	-0,07
5VE	0,31	-0,01	0,50	0,05	-0,71	-0,48	0,02	0,66	0,29	-0,73	0,42	-0,16
6VE	0,18	0,14	0,62	0,17	-0,80	-0,56	-0,14	0,62	0,22	-0,69	0,42	-0,21

Variable	Correlations: FPI vs. HR											
	Bold numbers on a grey background – correlations are significant at $p < .05$											
	N = 13											
	FPI 1	FPI 2	FPI 3	FPI 4	FPI 5	FPI 6	FPI 7	FPI 8	FPI 9	E	N	M
1HR	0,18	-0,42	-0,15	0,04	0,03	-0,15	-0,19	0,38	0,29	-0,23	0,00	0,09
2HR	0,67	-0,52	-0,19	-0,24	-0,52	-0,23	0,10	0,76	0,10	-0,62	-0,18	-0,49
3HR	0,65	-0,20	0,17	-0,03	-0,55	-0,42	0,08	0,61	0,06	-0,53	0,37	-0,46
4HR	0,46	-0,49	-0,08	0,13	-0,13	-0,43	0,07	0,46	0,14	-0,31	0,02	-0,07
5HR	0,33	-0,43	-0,04	0,10	-0,16	-0,51	-0,15	0,38	0,25	-0,33	0,00	0,10
6HR	0,24	-0,35	-0,06	0,15	-0,09	-0,51	-0,27	0,27	0,26	-0,21	-0,03	0,19

Variable	Correlations: FPI vs. O2											
	Bold numbers on a grey background – correlations are significant at $p < .05$											
	N = 13											
	FPI 1	FPI 2	FPI 3	FPI 4	FPI 5	FPI 6	FPI 7	FPI 8	FPI 9	E	N	M
1O2	0,37	0,09	0,57	0,20	-0,67	-0,42	0,10	0,61	0,13	-0,57	0,55	-0,22
2O2	-0,05	-0,50	-0,31	-0,05	0,42	0,41	0,09	-0,12	-0,47	-0,01	-0,49	-0,06
3O2	0,38	0,15	0,66	0,26	-0,65	-0,46	-0,01	0,53	0,18	-0,47	0,51	-0,07
4O2	0,27	-0,05	0,58	0,16	-0,72	-0,54	0,04	0,69	0,31	-0,58	0,37	-0,07
5O2	0,27	-0,05	0,51	0,02	-0,69	-0,44	0,08	0,64	0,36	-0,61	0,35	-0,03
6O2	0,24	0,09	0,61	0,11	-0,72	-0,46	0,04	0,57	0,30	-0,53	0,42	-0,04

Variable	Correlations: FPI vs. CO2											
	Bold numbers on a grey background – correlations are significant at $p < .05$											
	N = 13											
	FPI 1	FPI 2	FPI 3	FPI 4	FPI 5	FPI 6	FPI 7	FPI 8	FPI 9	E	N	M
1CO2	0,23	0,05	0,57	0,07	-0,78	-0,50	0,14	0,73	0,26	-0,72	0,55	-0,29
2CO2	-0,13	-0,50	-0,44	-0,08	0,53	0,46	0,08	-0,21	-0,43	0,10	-0,57	-0,02
3CO2	0,35	0,05	0,61	0,31	-0,60	-0,44	0,03	0,60	0,14	-0,53	0,51	-0,13
4CO2	0,21	-0,25	0,48	0,20	-0,59	-0,50	0,08	0,74	0,17	-0,65	0,29	-0,14
5CO2	0,28	-0,05	0,50	0,11	-0,72	-0,50	0,08	0,74	0,27	-0,69	0,43	-0,21
6CO2	0,18	0,06	0,61	0,23	-0,78	-0,58	0,00	0,70	0,21	-0,63	0,46	-0,22

FPI – Freiburg Personality Inventory, FPI1 – nervousness, FPI2 – spontaneous aggressiveness, FPI3 – depression, FPI4 – irritability, FPI5 – sociability, FPI6 – mildness, FPI7 – reactive aggressiveness, FPI8 – moderation (frustration), FPI9 – openness, E – extraversion, N – emotional lability, M – masculinity. For the other see the text to Fig. 1.

consumption and in glucose utilization. In brief, these new findings extended and specified our knowledge of the relationship between neuronal activity and energy metabolism in brain tissue, which is essential to the understanding of how the brain functions.

The new techniques of functional brain imaging play a crucial role in the study of cognitive activity of the brain. Appropriate combinations of the experimental strategies of cognitive psychology with various imaging techniques

actually examine how the brain function supports mental activities. However, they have a tiny drawback. They are intended only for researchers who are not suffering from lack of funds. Namely, this is not our case. Therefore, we decided to supplement our record of an ongoing EEG and event-related brain potentials to visual stimuli with a concurrent registration the Expired Minute Ventilation, Oxygen Consumption, Carbon Dioxide Production and Finger Pulse. We did it with the aim to assess the impact,

Abscissa: Average values of parameters V_E , HR, V_{O_2} and V_{CO_2} in the starting period (S), in the reference period (1), during the cognitive task solving (2) and in the first (3), second (4), third (5) and fourth (6) 30-second intervals of the recovery period. *Black circles* – average values, *Vertical bars* – 0.95 per cent confidence intervals, *Asterisk* – the average value differs ($p < .05$) from the average value calculated in the starting period.

Fig. 1. Dynamics of Expired Minute Ventilation (V_E), Heart Rate (HR), Oxygen Consumption (V_{O_2}) and Carbon Dioxide Production (V_{CO_2}) in the course of the experiment.

whatsoever it will be, of different cognitive activities on the basic respiratory and cardiovascular parameters. The obtained results are summarized in the present paper.

METHODS

The fifteen right-handed female students from the Medical Faculty of Palacký University in Olomouc participated in the experiment. Records of only 13 were analysed – one female stopped the experiment at her own request and another one was discarded because of her restlessness in the course of the experiment. All students were twenty-one-years old and they reported taking no medication and had no history of neurological, ophthalmological or systemic disease. Their vision was normal or corrected to normal. Written informed consent was obtained from all participants prior to the start of the experiment.

The experimental paradigm, procedures, features of visual stimuli and their relations to preassigned cognitive task were described in detail in our preceding paper¹⁶.

Therefore, we describe here only the method of data acquisition and the principles of their analysis.

Data acquisition

The ML870B80 Exercise Physiology System (ADInstruments Pty Ltd.) was used to record concurrently with EEG the cardio-respiratory and metabolic functions of our subjects during their cognitive activity in the course of the whole experiment. The system includes ML870 PowerLab 8/30 data acquisition unit with Chart software that provides control of ADInstruments hardware and includes a variety of analysis features such as XY plotting, differential, integral and spectral calculations. Other parts of the Exercise Physiology System are ML206 Gas Analyser, MLA246 Gas Mixing Chamber, ML141 Spirometer, ML309 Thermistor Pod and MLA240 Exercise Physiology Accessory Kit consisting of Respiratory Flow Head, Hans Rudolph Two-Way Non-Rebreathing Face Mask and other accessories. The Bio Amplifier ML132, Piezo-electric Finger Pulse Transducer MP100, Metabolic Module MLS240, Heart

Rate Variability Module MLS310 and ECG Analysis Module MLS360 for Chart software are also parts of Exercise Physiology System.

The Gas Analyser measured oxygen (%O₂) and carbon dioxide (%CO₂) concentrations in expired air sampled from the Gas Mixing Chamber. The Spirometer monitored airflow (l/s), the Thermistor Pod followed the temperature of respired air, the Bio Amplifier amplified finger pulses and the Chart software recorded all of these signals on the hard disk of a computer for later off-line replay and analysis.

Data analysis

Metabolic Module, Heart Rate Variability Module and ECG Analysis Module for Chart were used for off-line analysis of experimental data. Expired Minute Ventilation (V_E), Oxygen Consumption (V_{O_2}), Carbon Dioxide Production (V_{CO_2}) and Average Heart Rate (BPM) were ascertained for four periods: (1) rest or starting period, (2) reference period, (3) cognitive task solving period and (4) recovery period. Each period was defined by the type of presented visual stimuli and by the prearranged cognitive activity related to visual stimuli.

In the rest (starting) period no visual stimuli appeared while in the reference period a white blank oval on a dark background emerged on the screen (reference visual stimulus). The presence of reference stimuli did not require any cognitive activity of the subject. However, the presentation of other two visual stimuli (unfolded cube or net of sixteen small squares) exacted either solving of the cognitive task from subject (cognitive task solving period) or solely viewing the visual stimuli without any cognitive activity (recovery period) – the latter activity succeeded after the successful cognitive task solution. The average values of tested parameters were calculated during the recovery period four times, that is, for the first, second, third and fourth 30-second time intervals.

StatSoft software package (StatSoft, Tulsa, OK) was used for statistic processing of the metabolic and cardio-respiratory data. The score FPI parameters of Freiburg's Personality Inventory¹² were also considered in the statistic analysis.

RESULTS

The dynamics of V_E , HR, V_{O_2} and V_{CO_2} in the course of the experiment

Fig. 1 summarizes the dynamics of tested parameters in the course of the experiment. From it follows that the momentary functional state of subject's brain (i.e., period of the experiment) determines the average values of all measured parameters. During the cognitive task solving period the Expired Minute Ventilation (V_E), Oxygen consumption (V_{O_2}) and Carbon Dioxide Production (V_{CO_2}) reach the lowest average values while the average heart rate (HR) behaves reversely – it is highest in the cognitive task solving period. Furthermore, the average V_E , V_{CO_2} and HR values except V_{O_2} value differ significantly from

the average values of the same variable measured in the rest period.

The considerable decreases of V_E , V_{O_2} and V_{CO_2} during the cognitive task solving was replaced by the significant increase of all variables at the beginning of the recovery period – all averages at the first 30-second interval of the recovery period are significantly higher than in the rest period and cognitive task solving periods. HR shows a similar dynamics also but contrary to other tested parameters, HR is lower at the beginning of the recovery period than it was in the period of cognitive task solving.

From Fig. 1 it also follows that changes of all tested variables evoked by mental load during cognitive task solving rapidly disappear during the first minute of the recovery period except V_{O_2} – the latter does it only in the third 30-second interval. On the other hand, HR behaves in the recovery period differently – in the third and fourth 30-second intervals it reaches even significantly lower average values than in the rest period.

Participants' personality traits and V_E , HR, V_{O_2} and V_{CO_2} changes in the course of the experiment

The correlation analysis of our data revealed that tested cardiovascular (HR) and metabolic (V_E , V_{O_2} , V_{CO_2}) parameters are in relation to some personality traits of the subject. These were especially FPI parameter 3 (depression), FPI5 (sociability), FPI8 (moderation), E (extraversion) and in some cases also parameter N (emotional lability) that in majority of the experiment's periods affected the magnitude of V_E , V_{O_2} and V_{CO_2} increase/decrease against the average value of the same parameter in the rest (starting) period of the experiment (see Table 1). Table 1 also demonstrates that the FPI3 and FPI8 score show a direct relation to the magnitude of increase/decrease of tested variables while the FPI5 and E score show an indirect relation. The N score correlates negatively only with V_E and V_{CO_2} in the cognitive task solving period. In this context it must be emphasized that N (emotional lability) represented only one FPI parameter that correlated with metabolic variables in the cognitive task solving period of the experiment.

However, much freer are the relations between subject's personality traits and HR changes. It was shown that the score of only two subject's personality traits (FPI1 – nervousness and FPI8 – moderation) from twelve established correlate positively with the size of increase of HR in two periods of the experiment, i.e. in the task solving period and in the first 30-second interval of the recovery period. On the other hand, the third of the twelve FPI parameters (extraversion) shows an indirect relation to the HR changes during the task solving period.

DISCUSSION

The fact that average values of expired minute ventilation (V_E), oxygen consumption (V_{O_2}) and carbon dioxide production (V_{CO_2}) were in our subjects markedly lower during the cognitive task solving period than during the rest period is unexpected and in some ways surprising.

We are surprised because there is a numerous of studies^{see e.g. 6, 7, 10, 14, 15, 17, 18, 20, 22} demonstrating unequivocally that energy metabolism in the cerebral tissues is, as in other tissues, closely coupled to its functional activity; the higher the functional activity of the brain is the higher energy supply is required.

Allowing for these facts and information that under normal physiological conditions, the majority of energy required for the ATP generation by mitochondria in the adult brain is supplied almost exclusively via complete oxidative metabolisms in the TCA cycle²³, the subject's oxygen consumption during their high mental activity related to cognitive task solving ought to be increased. Consistent with this is also the conclusion of Gjedde et al.⁸ that resulted from a detailed analysis of published data describing the responses of brain metabolism to different somatosensory and visual stimuli. The authors note that simple somatosensory and visual stimuli with little information content produce a smaller increase in oxygen consumption than do complex somatosensory stimuli and the motor activity based on a qualitative evaluation of the information content of the stimuli. The arising of complex stimuli is followed by an increase in both blood flow and oxygen consumption, i.e. the complex stimulation is accompanied by a significant increase in the brain oxidative metabolism.

The answer to the question why the respiratory parameters behaved differently in our experiment than we expected is not easy. The closest to the truth will be the assumption that respiratory variables measured by us during the cognitive task solving period predicate about the whole-body metabolic rate of an organism than about the energy metabolism of the brain itself. The changes of the respiratory pattern that we observed during the cognitive task solving periods support this claim. The decrease in respiratory rate and decrease in tidal volumes were typical for each of cognitive task solving periods. The effect of a cognitive task performance (solving a puzzle) on the respiratory pattern was also described by Bell et al.¹. They showed that performance of a cognitive task decreases the initial phase of exercise hyperpnoea. Therefore it seems that the smaller respiratory work related to the changed respiratory pattern of subjects in the cognitive task solving period could account for the lower oxygen consumption in this phase of the experiment.

Contrary to respiratory variables, the heart rate during cognitive task solving periods behaved according to expectation, i.e. its average values were significantly higher during the cognitive task solving than during the reference period. Several other authors described similar dynamics of the heart rate during mental load too^{see e.g. 2, 3, 4, 5, 11}.

The increased activity of the sympathetic nervous system was probably the main cause of subjects' high heart rate when they solved the cognitive tasks. The correlation analysis of our data (the heart rate increase vs. personality traits) proved this assumption. The size of increase in the heart rate during the cognitive task solving correlated positively with the score of nervousness (FPI1) and frustration (FPI8) while the score of extraversion (E) showed negative correlation. Thus, subjects with personal-

ity traits related to higher sympathetic activity showed a strong increase of the heart activity during the cognitive task solving and vice versa. Respiratory variables showed similar dependence – they correlated positively with the score of depressiveness (FPI3) and frustration (FPI8) and negatively with the score of sociability (FPI5) and extraversion.

In conclusion, the presented results show that the actual mental load affects the average values of respiratory (V_E , V_{O_2} and V_{CO_2}) and cardiovascular (HR) parameters. It appears, however, that changes of respiratory variables predicate about the whole-body metabolic rate of an organism rather than about the energy metabolism of its brain. Contrary to respiratory parameters, the actual heart rate during the solving of cognitive tasks has undoubtedly a tighter relation to brain's energy metabolic rate because it affects the oxygen supply of the brain.

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